Ten promising pathways to GHG emission reduction in the global food system

Nathanaël Pingault
Christopher Martius

OCCASIONAL PAPER 3

Occasional Paper 3

Ten promising pathways to GHG emission reduction in the global food system

Nathanaël Pingault
CIFOR-ICRAF

Christopher Martius
CIFOR-ICRAF

CIFOR-ICRAF

Occasional Paper 3

DOI: 10.17528/cifor-icraf/008836

Pingault N and Martius C. 2023. *Ten promising pathways to GHG emission reduction in the global food system*. Occasional Paper 3. Bogor, Indonesia: CIFOR (Center for International Forestry Research); and Nairobi, Kenya: World Agroforestry (ICRAF).

Photo by Aris Sanjaya/CIFOR
CBCF Project, Yogyakarta

CIFOR
Jl. CIFOR, Situ Gede
Bogor Barat 16115
Indonesia
T +62 (251) 8622-622
F +62 (251) 8622-100
E cifor@cgiar.org

ICRAF
United Nations Avenue, Gigiri
PO Box 30677, Nairobi, 00100
Kenya
T +254 20 7224000
F +254-20- 7224001
E worldagroforestry@cgiar.org

cifor-icraf.org

Table of content

List of tables

Tables

Acknowledgements

Financial support for this study was provided through Mitigate+: Research for Low Emissions Food Systems. We would like to thank all funders who supported this research through their contributions to the CGIAR Trust Fund.

1 Introduction, scope and methodological considerations

According to the latest assessment report of the Intergovernmental Panel on Climate Change global average surface temperatures are now 1.09°C higher than in the pre-industrial era [range 0.95 – 1.2°C]. GHG emissions from human activities are now unequivocally considered as the main driver of this global warming (IPCC 2021).

Food systems "gather all the elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production, processing, distribution, preparation and consumption of food, and the outputs of these activities, including socio-economic and environmental outcomes" (HLPE 2014). They are responsible of 23 – 42% of total net anthropogenic emissions (Babiker et al. 2022) and this share could increase in the coming decades when transitioning towards a low-energy and low-carbon economy and under a need to ensure food security and nutrition for a growing population (Dixson-Declève et al. 2022). If nothing changes, agriculture and land use related emissions are expected to increase by 30-40% by 2050, driven by population and income growth as well as changes in diets (Mbow et al. 2019).

Hence, even if fossil fuel emissions were stopped now, without radical transformation in global food systems, both on the supply- and demand-sides, it could become impossible to reach the Paris Agreement +1.5°C target and even to remain below the +2°C target by the end of the century (IPES-Food 2016; HLPE 2017; Niles et al. 2018; Clark et al. 2020; Amenchwi et al. 2023). However, emissions reduction efforts in food systems should not endanger food security and nutrition, in particular for the most vulnerable populations in developing countries. This explains why many countries, particularly from the South are reluctant to impose constraining emission reduction targets in agriculture and food production. In this document we will highlight ten promising, yet so-far uncharted and under-explored pathways to reduce GHG emissions and boost the transformation required in food systems without threatening food security and nutrition. These suggested pathways do not add up; instead, they sometimes overlap, providing a window on sometimes novel entry points rather than a systematic map to emissions-zero. They are intended to instigate a debate, particularly in policy and decision-maker circles, on the best opportunities – 'low-hanging fruits' – towards rapid drawdown of emissions, while more time-consuming, costly or technically elaborate approaches are being developed. Instead of looking at the largest emission sources and narrowly focusing on addressing these, we instead intend to set in motion activities that explore and respond to opportunities to effectuate efficient and effective mitigation option.

1.1 Food system GHG emissions

Following guidelines issued by the IPCC (2006, 2019a), GHG emissions are usually measured and analyzed by sectors. The IPCC (2006, 2019a) distinguishes four main economic sectors – Energy; Industrial Processes and Product Use (IPPU); Agriculture, Forestry and Other Land Use (AFOLU); and Waste – and developed specific GHG inventory guidelines for each sector. Although more than 70% of food system emissions used to come from the AFOLU sector (Mbow et al. 2019, Crippa et al. 2021), GHG emissions beyond farmgate, related to pre- and post-production activities, span over all the other sectors (i.e. Energy, IPPU and waste). The share of non-AFOLU sectors in total food system emissions has increased from 28% in 1990 to 39% in 2018 (Babiker et al. 2022, see also Table 1**).** Hence, to efficiently reduce food system

Table 1. Food system net anthropogenic GHG emissions. Adapted from Mbow et al. (2019) and Babiker et al. (2022).

Food system component (and main GHG emitted)	Net emissions in GtCO2eq.yr^{-1}: central estimation [range] (uncertainty in %) {central share of food system emissions in %}	
	Mean 2007-2016 (Mbow et al. 2019)	2018 (Babiker et al. 2022)
Agriculture (CH4, N2O)[a]	6.2 [± 1.9] (~ 30%) {41.9%}	6.3 [2.6-11.9] (~ 75%) {37.1%}
Land use, land use change and forestry (CO2)	4.8 [± 2.4] (~ 50%) {32.4%}	4 [2.1-5.9] (~ 50%) {23.5%}
Beyond farmgate[b] - non AFOLU sectors – (CO2)	3.8 [± 1.3] (~ 34%) {25.7%}	
Energy		3.9 [3.6-4.4] (~ 10%) {22.9%}
Waste		1.7 [0.9-2.6] (~ 50%) {10%}
IPPU		0.9 [0.6-1.1] (~ 30%) {5.3%}
Total food system emissions	14.8 [± 3.4] (~ 23%) {100%}	17 [13-23] (~ 30%) {100%}

a Emissions from aquaculture and fisheries may represent about 0.58 GtCO2eq per year, i.e. about 10% of total agriculture emissions (Barange et al. 2018). These global estimates are not included in agriculture emissions in Table 2 because they are small and uncertain and may not be included in national GHG inventories (Mbow et al. 2019).

b Following IPCC guidelines, pre-production activities fall under industry (fertilizers manufacturing etc.), and, hence, belong to the non-AFOLU sectors.

emissions, it is important to adopt an integrated perspective that considers the whole food supply chain (from pre-production, on-farm and post-production activities, including waste management and disposal) and spans across the four IPCC economic sectors.

In its latest assessment report (Babiker et al. 2022), the IPCC estimated that, in 2018, the global food system emitted 17 GtCO2eq per year [range: 13 – 23] associated with food production, processing, distribution, preparation and consumption and with the management of food system residues.[1] Mbow et al. (2019) grouped these net anthropogenic food system emissions in three main categories (agriculture; land use change and forestry; and emissions beyond farmgate, see Table 1), while Babiker et al. (2022) provide a sectoral disaggregation of food system emissions across the four IPCC economic sectors (see Table 1).

Food system emission estimations remain highly uncertain. The first two components identified in Table 1 (agriculture and land use changes) are considered as well-known and well quantified, based on an ample and increasing body of literature (Smith et al. 2014, Mbow et al. 2019). However, uncertainties associated with agriculture and land use have been estimated respectively at around 30% and 50% (Smith et al. 2014), in line with the uncertainties estimated by Mbow et al. (2019) and reported in Table 1. The latest IPCC estimation for agriculture emissions has an even larger uncertainty associated to it (see Table 1: Babiker et al. 2022). These uncertainties are largely explained by our limited understanding of the complex spatial and temporal dynamics at stake, of the biophysical and biological processes involved in land-climate interactions and feedback loops, as well as by the limitations of our estimation models. Food system emissions beyond farmgate could be even more uncertain due to lack of sufficient studies (Niles et al. 2018; Mbow et al. 2019).

The global figures shown in Table 1 hide important disparities across countries. Crippa et al. (2021) estimated for instance that, in 2015, AFOLU emissions represented 73% of total food system emissions in developing countries while, in industrialized countries, non-AFOLU emissions were predominant (53% of the total). Specific national GHG emission reduction strategies, adapted to the national biophysical

---

[1] This paper, which focuses on reducing net anthropogenic GHG emissions, do not consider the “natural response of land to human-induced environmental change”, i.e. the non-anthropogenic natural land sink evaluated by the IPCC (2019b) at about -11.2 ± 2.6 GtCO2 per year.

and socioeconomic context, as well as to national priorities and needs, are needed to account for this disparity. Such strategies must be grounded on accurate national level data on food system emissions.

Currently, two main datasets exist with national level data on food system emissions and a global coverage allowing cross country comparisons. First, the EDGAR Food dataset[2], developed by the European Joint Research Centre (JRC), estimates, across the four economic sectors, which emissions can be attributed to food systems. This estimation relies on the JRC EDGAR dataset[3] which provides annual emissions data by sector, country and GHG[4] as well as on a matrix of food system shares (SFSs) (Crippa et al. 2021). EDGAR Food provides annual emission data since 1990 by GHG, country and food system stage.[5]

Second, the FAOSTAT dataset,[6] developed by FAO, is a global and comprehensive dataset providing country level data on food security and nutrition, food supply and food balance, land use, agricultural inputs, agricultural and forestry production and trade and related GHG emissions. Emission data in FAOSTAT, disaggregated by year, country, gas and economic sectors[7] are available since 1961. In FAOSTAT, agrifood system emissions, from AFOLU and non-AFOLU sources, are identified and grouped in three main categories (land use change, farmgate, pre- and post-production), further disaggregated as shown in Table 2 below.

FAOSTAT figures given in Table 2 are globally consistent with the IPCC estimations as total agrifood systems emissions fall in the range estimated by the IPCC (Mbow et al. 2019; Babiker et al. 2022) and indicated in Table 1. Overall, consistency is maintained for the three main categories as farmgate and land use change emissions fall in the respective ranges estimated by the IPCCC (Mbow et al. 2019; Babiker et al. 2022). Non-AFOLU emissions beyond farmgate are a bit higher than the upper range of IPCC estimations in Mbow et al. (2019) but still of the same order of magnitude. This slight difference is not surprising considering the high uncertainty, highlighted above, and lack of studies around the attribution to food systems of a proportion of the emissions from non-AFOLU sectors emissions.

FAOSTAT categorizations illustrated in Table 2, and the different individual sources of GHG emissions, are closely based on IPCC classification.[8] In particular, "savanna fires" corresponds to "prescribed burning of savanna", classified under Agriculture by the IPCC. Most food system emissions beyond farmgate come from the IPCC Energy sector, except "food retail" F-gases emissions (included in the IPPU sector) and "food systems waste disposal" (including in the Waste sector). Two significant differences, however, can be noted. First, the item "drained organic soils", included by FAOSTAT under "farmgate emissions" is split by the IPCC between CO2 emissions from drained organic soils classified under Land Use, Land Use Change and Forestry (LULUCF), and N2O emissions classified under Agriculture. Second, "on-farm energy use", included by FAOSTAT in "farmgate emissions", is classified by the IPCC in the Energy sector. Corrected farmgate emissions, excluding "drained organic soils (CO2)" and "on-farm energy use" amount globally to about 6 GtCO2eq per year while corrected land use change emissions, including "drained organic soil (CO2)" reach around 4 GtCO2eq per year. These two figures are closer to Mbow et al. (2019) central estimations indicated in Table 1.

---

[2] For more information see: https://edgar.jrc.ec.europa.eu/edgar_food

[3] EDGAR stands for "*Emissions Database for Global Atmospheric Research*" which provides annual emission data not only for GHGs but also air pollutants over the period 1970-2021. The EDGAR Food dataset is based on EDGAR v6.0. A more recent version (EDGAR v7.0) is now available. For more information, see: https://edgar.jrc.ec.europa.eu/emissions_data_and_maps

[4] i.e. CO2, CH4, N2O and F-gases.

[5] EDGAR Food distinguishes 6 food system stages, from (1) Land use and Land-Use Change (LULUC), (2) Production, (3) Processing, (4) Distribution (including packaging, transport and retail), (5) Consumption (including domestic food preparation activities) and (6) End of life (waste).

[6] Accessible online at: https://www.fao.org/faostat/en/#data

[7] i.e. AFOLU, Energy, IPPU, Waste, International bunkers and Other.

[8] For more details, see the FAOSTAT methodological note on GHG emissions released in October 2022 and accessible at: https://fenixservices.fao.org/faostat/static/documents/GT/GT_e.pdf

Table 2. World agrifood systems GHG emissions in 2020[a]

All GHG emissions (2020)	GtCO2eq	%
Agrifood systems	16.14	100.0%
Land use change	3.15	19.5%
Net Forest conversion	2.95	18.2%
Fires in humid tropical forests	0.16	1.0%
Fires in organic soils	0.05	0.3%
Farmgate	**7.39**	**45.8%**
Enteric Fermentation	2.85	17.7%
Drained organic soils, including:	0.92	5.7%
Drained organic soils (CO2)	0.83	5.1%
Drained organic soils (N2O)	0.09	0.6%
Manure left on Pasture	0.77	4.8%
Rice Cultivation	0.69	4.3%
Synthetic Fertilizers	0.63	3.9%
On-farm energy use	0.53	3.3%
Manure Management	0.40	2.5%
Savanna fires	0.21	1.3%
Crop Residues	0.19	1.2%
Manure applied to Soils	0.17	1.0%
Burning - Crop residues	0.04	0.2%
Pre- and post-production	**5.60**	**34.7%**
Food systems waste disposal[b]	1.26	7.8%
Food Household Consumption	1.25	7.8%
Food Retail	0.89	5.5%
Food Transport	0.54	3.3%
On-farm electricity use	0.50	3.1%
Food Processing	0.47	2.9%
Fertilizers Manufacturing	0.39	2.4%
Food Packaging	0.30	1.8%

a Emissions in CO2eq are calculating using the Global Warming Potentials with a 100-year time horizon (GWP100) defined in the IPCC fifth Assessment Report (AR5, IPCC 2014), i.e. a GWP100 of 28 for CH4 and of 265 for N2O.

b This includes only emissions associated with the end-of-life phase, waste management and disposal, but excludes the emissions generated by the production and transformation of food that is finally lost or wasted.

Source: FAOSTAT (See: https://www.fao.org/faostat/en/#data/GT (accessed on 20/01/2023))

1.2 Mitigation potentials in agriculture and land use

Developing datasets on agricultural emissions and mitigation potentials, consistent over large spatial and temporal scales but disaggregated by source of emissions, greenhouse gas or geographical scales, and implementing efficient land-based mitigation strategies is challenging because the land-use sectors: (i) cover a wide range of production systems in many different ecosystems and landscapes; (ii) build upon complex biological processes, with many interactions and feedback loops, often non-linear and still imperfectly understood; and (iii) involve a multiplicity of actors at different scales, among which many smallholders (Beach et al. 2015; Jia et al. 2019; HLPE 2018). Yet, in recent years, many studies (including for instance: Griscom et al. 2017; Roe et al. 2019, 2021) tried to estimate the mitigation potential of natural climate solutions or, in other words, land-based mitigation options. According to Roe et al. (2019), the global land-based mitigation potential amounts to 15 GtCO2eq per year, i.e. about 30% of the global mitigation effort needed by 2050 to reach the +1.5°C target. The IPCCC Sixth Assessment Report (Nabuurs et al. 2022) found a global land-based mitigation potential of 8–14 GtCO2eq per year over the period 2020–2050 assuming carbon prices below USD 100 per tCO2eq, about 30–50% of which could be achieved at very low carbon price (below USD 20 per tCO2eq).[9]

The scientific literature usually distinguishes: (i) the technical mitigation potential, i.e. the overall biophysical potential available with current technologies; (ii) the cost-effective economic potential, available at reasonable price (e.g. up to USD 100 per tCO2eq); (iii) the sustainable potential, constrained by social and environmental safeguards; and (iv) the feasible potential, constrained by environmental, socio-cultural, and/or institutional barriers (Nabuurs et al. 2022). It also acknowledges that mitigation potentials are even more uncertain than GHG emissions because of additional assumptions on, e.g., technical innovation trends or carbon price evolution, and because of additional methodological issues.

---

[9] All the mitigation potentials from Roe et al. (2019) and Nabuurs et al. (2022) reported in this paper are expressed in GtCO2eq per year and calculated over the period 2020-2050.

Table 3. Global cost-effective economic mitigation potentials (GtCO2eq per year)[a]

Mitigation potentials	Sectoral approach	Modelling approach
Production side measures		
Agroforestry	1.12	
Biochar application	1.81	
Enhance land sequestration		0.95
Soil carbon in croplands	0.92	
Soil carbon in grasslands	0.89	
Enteric Fermentation	0.10	0.97
Nutrient management	0.22	0.31
Manure Management	0.09	0.24
Rice Cultivation	0.17	0.19
Grassland and savanna fire management	0.03	
Demand side measures		
Healthy diets	1.43	
Food waste	0.45	
Clean cookstoves	0.11	

a Available up to USD 100 per tCO2eq.

Source: adapted from Roe et al. (2021).

In particular, all mitigation options often interact among each other, creating synergies and trade-offs. For instance, reducing meat consumption would impact the population of live animals, thus reducing also the emissions linked to enteric fermentation and net forest conversion. Hence, the potentials calculated for each mitigation option may vary according to the emissions considered and may not add-up, at sectoral level or across sectors, leading to overestimating the global food system mitigation potential. Another limitation is the small number of mitigation options considered in current modelling exercises, leading to underestimating the global food system mitigation potential (Roe et al. 2021; Nabuurs et al. 2022).

Based on previous studies and on FAOSTAT data, Roe et al. (2021) estimated national, technical and economic mitigation potentials for 20 land-based measures in over 200 countries, following a sectoral "bottom-up" sectoral approach based on a literature review and a modelling "top-down" approach and comparing the results of both (see Table 3). They found a cost-effective land-based global mitigation potential of 8 to 13.8 GtCO2eq per year between 2020 and 2050, consistent with previous studies (e.g. Griscom et al. 2017; Roe et al. 2019). They also realized a quantitative feasibility assessment of this mitigation potential in each country, across the six dimensions of feasibility - economic, institutional, geophysical, technological, socio-cultural and environmental-ecological – as defined by the IPCC (de Coninck et al. 2018).

Many recent assessments (including Griscom et al. 2017, 2020; Roe et al. 2019, 2021) provide quite consistent figures but focus only the production and consumption phases. They cover the main land-based mitigation options on the production-side, as well as change in diets and food losses and reduction of food losses and waste on the demand-side. But they do not consider the whole food supply chain (from production to consumption), often arguing that pre- and post-production activities (beyond farmgate) represent a small part of food system GHG emissions.

1.3 Purpose of this paper

As shown above, food systems emissions are not restricted to the land-based sector and span over the whole food supply chain, from cradle to grave, including in particular input provision, transport, storage, processing, distribution and waste management. Moreover, a decision taken at any step of the food value chain will necessarily impact the others. Hence, this paper suggests adopting a whole food system perspective to identify so-far uncharted mitigation options, as well as associated synergies and trade-offs, along the whole food value chain, from production to consumption. This paper proposes to go beyond the usual land use change and bioenergy perspective and focus on less-trodden pathways for emission reductions across the whole food system. Although they may represent lower mitigation potentials, these pathways should not be overlooked because they may offer opportunities that are more easily addressed, aligned with technical potential or capacity, or national and regional preferences, than the more classic land-based or 'nature-based' solutions.

The discussions above (see in particular Tables 2 and 3), as well as previous reviews such as Amenchwi et al. (2023), enable us to identify ten promising emission reduction pathways:

1. Shift to more sustainable and healthier **diets**
2. Improve **waste** management
3. Improve **energy** use across food value chains
4. Optimize **cold-chain** efficiency in food systems
5. Reduce emissions from **enteric fermentation**
6. Optimize **manure** management
7. Reduce emissions from **synthetic fertilizers** manufacturing and application
8. Improve **rice** cultivation
9. Increase **soil organic carbon** stock
10. Encourage **agroforestry** uptake and upscale

The performance (mitigation potential, co-benefits and risks, implementation modalities) of most of these ten food system mitigation pathways is highly dependent on local biophysical, socio-economic and institutional conditions, highlighting the need to move away from top-down silver-bullet solutions imposed by external experts and adopt an options-by-context approach, giving a central role to local actors and their local knowledge (Sinclair and Coe 2019). Innovative, place-based, horizontal peer-to-peer learning models, as well as multi-stakeholder platforms and communities of practice will be instrumental to ensure the scalability of these context-specific mitigation pathways (HLPE 2018, 2019).

These ten pathways are further explored in the following sections, from the demand to the production side, keeping in mind that with no profound changes in consumer mentalities and behaviors there will be no real transformation in current food systems and that a change in demand will naturally impact GHG emissions upstream, at earlier stages of the food value chain.[10]

---

[10] See for instance the links already discussed above between a shift in diet and GHG emissions from enteric fermentation or net forest conversion.

2 Shift to more sustainable and healthier diets

Unsustainable and unhealthy diets carry a huge burden for human health and the environment. Globally, in 2017, 10-12 million deaths are associated with unhealthy diets (GBD Collaborators 2019). Overweight and obesity, as major risk factors for non-communicable diseases (NCDs), were responsible of about 4 million deaths worldwide in 2015 (GBD Collaborators 2017). WHO also identified overconsumption of red and processed meat as a probable factor of risk in certain forms of cancer.[11]

Current diets and the associated food systems are deemed very resource-intensive, unsustainable in the long term because of their excessive environmental footprint. According to Poore and Nemecek (2018), the food system uses 87% of all agricultural land for food and feed production,[12] two thirds of freshwater withdrawals irrigation, and is responsible for about 26% of total GHG anthropogenic emissions, 32% of acidifying emissions and 78% of eutrophying emissions, with drastic impacts on biodiversity, and ecosystem structure, composition, health, functionality, and resilience.

Demand-side mitigation options such as changes in diet could hold a greater mitigation potential than production-side measures (Niles et al. 2018). Shifting to more sustainable and healthier diets could follow many complementary pathways among which three are briefly discussed below:

- Reduce meat and animal-product consumption.
- Limit overconsumption and shift to healthier diets.
- Develop short value chains and locally sourced diets

2.1 Reduce meat and animal product consumption

Over the past 60 years, animal products consumption increased rapidly, following population and income growth and changes in diets (HLPE 2016). Between 1961 and 2020 meat global food supply increased from 23 to 43 kg per capita per year (FAOSTAT)[13] and this increase is sharper in emerging and developing countries. Animal products, especially ruminant meat, generally have much higher environmental (carbon, land and water) footprints than vegetal products. Livestock (meat and dairy) related emissions,[14] represent almost 60% of global food system emissions (Pörtner et al. 2021). Globally, livestock is the first user of land resources. The livestock sector covers nearly 80% of total agricultural land for feed crops, meadows and pastures but produces only 33% of proteins, and 17% of the dietary energy intake (HLPE 2016; FAO 2018a; UNEP 2019). This highlights the blatant inefficiency of current land use patterns. The environmental footprints of animals are often higher by unit of product than that of their vegetal counterparts. While milk and eggs, pig and poultry meat are comparable to vegetal proteins in terms of land-use and GHG emissions (respectively, around 10 m2 and 10 kgCO2eq per 100g protein, or less), ruminant meat has much higher footprints, e.g. up to 164 m2 and 50 kgCO2eq per 100g of protein for bovine meat (Poore and Nemecek 2018). Livestock is also a major user of water resources for irrigation of feed crops, production and processing. Meat water footprint can reach up to 112 L per g protein for beef and 34 L for chicken, against only 19 and 16 L per g protein respectively for pulses

---

[11] See: https://www.who.int/news-room/q-a-detail/cancer-carcinogenicity-of-the-consumption-of-red-meat-and-processed-meat

[12] The remaining 13% being devoted to non-food uses, such as bioenergy, textile crops, wool, or leather.

[13] See: https://www.fao.org/faostat/en/#data/FBS (accessed on 7 March 2023).

[14] From livestock related land-use changes, feed production, enteric fermentation, animal waste, livestock transport and processing.

and oil crops (Mekonnen and Hoekstra 2011, 2012).[15]

Reducing meat and animal product consumption, especially in high-income countries, could thus be a powerful win-win lever to reduce GHG emissions, land and water footprints while, at the same time, providing multiple co-benefits for human health, food security and nutrition and biodiversity, and increasing ecosystems' resilience and adaptive capacity. Poore and Nemecek (2018) estimated that adopting a vegan diet could reduce the food system footprints by 76% for land use, up to 32% for freshwater withdrawals and 49% for GHG emissions. Westhoek et al. (2014) found that halving consumption of meat, eggs and dairy products in the European Union could reduce NH3 emissions by 40%, non-CO2 GHG emissions by 25–40%, and cropland used for food production by 23% while lowering health risks linked to overconsumption of animal products, or related to consumption of mass-produced meat with its problems of hormone loads etc. Overall, based on a thorough literature review, Roe et al. (2019) estimated the global mitigation potential of a shift to plant-based diets in the range of 0.7-8 GtCO2eq per year, the upper limit of this range (from Springmann et al. 2016) corresponding to the worldwide adoption of a vegan diet. Such a shift in diets could cover one-fifth of the mitigation effort required to respect the +2°C climate target and one-quarter of available low-cost options (Griscom et al. 2017). Traditional diets such as traditional Indian diets where pulses account for a higher share of protein intake are worth being preserved and promoted as they offer valuable examples of how such a diet shift could be implemented. In addition to reduction in GHG emissions, spared land, no longer useful for food production, if appropriately managed and restored, could be used to enhance carbon capture and storage for a potential estimated at 8.1 GtCO2 per year (Poore and Nemecek 2018).

On the other hand, livestock is an important source of nutrients and income for vulnerable groups in developing countries, in particular for pastoral communities in drylands were opportunities for alternative agricultural or other economic activities are very limited. Beef contains twice as much protein as beans for instance, and 2.5 times more iron. As adult humans can eat only about 2.5 kg of food per capita per day, there is a need to prioritize the most nutritious food (Mbow et al. 2019). Meat and animal products can thus make a critical contribution to food security and nutrition, particularly in countries, such as Colombia or Kenya, where the livestock sector is important and where undernutrition and child stunting are still prevailing at high rates. Livestock also provides multiple economic and environmental benefits, particularly in traditional pastoral systems in developing countries. Ruminants are able to transform low quality-forage and cellulosic biomass not directly digestible by humans in nutritious food, thus contributing to the valorization of marginal lands, unsuitable for cultivation. Livestock also serves as an essential source of draught power and of organic fertilizers and investment asset, enhancing the social status of its owner. Livestock breeding thus makes an essential contribution to food security and nutrition and livelihoods, as well as to the preservation and restoration of natural or semi-natural ecosystems (Weiler et al. 2014; HLPE 2016; Mbow et al. 2019; Babiker et al. 2022).

In conclusion, future climate and land use scenarios will vary drastically depend on the assumptions made on animal product consumption levels and trends. Yet, the complex links, both positive and negative, between animal source foods, human health, food security and nutrition, land use, biodiversity and climate change, and their variation across countries, products and farming systems, will make it challenging to define an optimal level of animal product consumption. This will be all the more difficult that this optimal level will have to be adapted to the specific (social, environmental, economic and nutritional) context of each country (HLPE 2016, 2017). In particular, the recommendations regarding the evolution of animal product consumption cannot be the same in high-income and low-income countries. Hence, the question is not about reducing read meat consumption everywhere for everyone but about encouraging the adoption of sustainable animal production and consumption practices adapted to a wide diversity of farming and food systems, cultures, and socio-economic contexts (HLPE 2017; Willet et al. 2019; Mbow et al. 2019). Innovative animal food products, such as insects, with much lower carbon, land

---

[15] See also: https://waterfootprint.org/en/resources/waterstat/product-water-footprint-statistics/

and water footprints,[16] shorter reproduction periods, and higher nutritional value and feed-to-protein conversion ratio, are rapidly becoming available and could open new pathways towards more sustainable diets (FAO 2013a; HLPE 2017; Mbow et al. 2019; Babiker et al. 2022). Innovative alternatives to meat, including insects, algae, microbial proteins or cultured meat, are being developed some of which could become economically competitive within the next two decades (e.g. Kumar et al. 2017; Pikaar et al. 2018; Gerhardt et al. 2019; Leger et al. 2021; Babiker et al. 2022).

2.2 Limit overconsumption and shift to sustainable healthy diets

"Sustainable healthy diets" are dietary patterns that "promote all dimensions of individuals' health and well-being; have low environmental pressure and impact; are accessible, affordable, safe and equitable; and are culturally acceptable" (FAO/WHO 2019). Healthy diets must respect the following four principles. They must: (i) contain foods and beverage that are safe to consume (safety); (ii) provide the adequate levels of food energy intake (quantity), (iii) and of macro- and micro-nutrients (quality); and (iv) include diverse nutrient-dense foods from the different basic food groups (diversity) (HLPE 2017). Food choices are determined by individual preferences and constrained by the food environment, i.e. "the physical, economic, political and socio-cultural context in which consumers engage with the food system to make their decisions about acquiring, preparing and consuming food" (HLPE 2017). This space of choice, when limited, may hamper the transition towards sustainable and healthy diets (Meybeck and Gitz 2017; HLPE 2017; Nabuurs et al. 2022).

Limiting overconsumption and shifting to healthier diets (poorer in salt, sugar, trans-fats, ruminant meat and ultra-processed food and richer in fruits, vegetables and whole grains) could provide multiple co-benefits for human nutrition and health, the climate and the environment (Mbow et al. 2019). Reducing the share of processed and ultra-processed foods in diet will reduce the GHG emissions associated with their processing, packaging and transport (Niles et al. 2018). Overconsumption (i.e. consumption exceeding the individual needs) can be assimilated to a waste of food and natural resources. In Australia for instance, about 33% of GHG emissions from the food system can be attributed to overconsumption (Hadjikakou 2017) and discretionary foods, which provide no essential nutrient, contribute almost 30% of GHG emissions in average diet (Hendrie et al. 2016). Alexander et al. (2016) estimated that if everyone on Earth adopted the average US diet, agriculture would need to cover almost twice the global habitable land area. In France, Vieux et al. (2012) calculated that avoiding overconsumption and aligning dietary energy intake with individual needs could save up to 11% of GHG emissions. Promoting a "deforestation-free" diets, by reducing the consumption of food commodities linked to deforestation[17], and promoting deforestation-free value chains, can decrease sensibly GHG emissions from land use changes (Amenchwi et al. 2023). Changes in diets could contribute to spare globally 4-25 million km^2 of land (Smith et al. 2020), more than the current cropland area and more than half the total agricultural land, reducing drastically the pressure on land, water and natural resources. Such spared land, if judiciously managed, could be used to enhance soil carbon sequestration, preserve biodiversity and promote ecosystem restoration, thus increasing ecosystems and communities' resilience to climate change and natural disasters.

Consumers, by encouraging low-impact products or farming systems can do a lot in reorienting food production. Food labels or food price incentives or disincentives, such as a carbon tax or a sugar tax, are crucial levers to orient consumer choices and support the transition towards healthier and more sustainable diets (HLPE 2017; WHO 2019; Babiker et al. 2022). Springmann et al. (2017) evaluated at 1 GtCO2eq per year the global mitigation potential of a carbon tax of food products of USD 52 per kgCO2eq. Higher food prices could reduce overconsumption and food waste but, on the other hand, might threaten food security of the most vulnerable. Pro-poor policies and safety nets can help manage this trade-off

---

[16] Above all if grown on agricultural residues, food waste or manure.

[17] According to Pendrill et al. (2019), the commodity groups that generate the highest deforestation are cattle meat, forestry products, oil palm, cereals and soybeans, with impacts varying across countries and commodities.

(Mbow et al. 2019). For instance, the additional revenue from a carbon tax could contribute to fund food-aid programmes in low-income countries (Hasegawa et al. 2018).

2.3 Develop locally sourced diets, short value chains and circular bioeconomy solutions

In line with the “food sovereignty” concept introduced during the 1996 UN World Food Summit, by *La Via Campesina,* an international peasant movement, many voices, from civil society or the scientific community, are calling for a paradigm shift, away from uniformity to diversity, away from our current globalized and industrialized food system, towards a diversity of re-localized food systems (HLPE 2016, 2017, 2019; IPES-Food, 2016). Re-localized food systems and short value chains can contribute to reduce the environmental footprint of international trade (estimated at 21% of total anthropogenic GHG emissions and 30% of global species threats, Pörtner et al. 2021). Short supply chains can also reduce the GHG emissions generated by food processing, storage, and transport over long distances, although in some cases, imported foods can have a lower carbon footprint than local foods. [18] The development of local and circular bioeconomy solutions can reduce food losses and waste and the dependence on external chemical inputs, in particular fertilizers or fossil fuels, as well as the associated GHG emissions and ecological footprints. Re-localized food systems, more adapted to local conditions, valorizing better the potential of local species and breeds, including neglected and underutilized species, can also improve dietary quality and diversity and generate more diversified, productive, resilient and adaptive local agroecosystems for enhanced food security and nutrition, livelihoods and biodiversity. Often more labor and knowledge intensive, such food systems can also contribute to create green and innovative jobs, preserve local and traditional knowledge and revitalize local economies in rural areas thus strengthening the livelihoods and resilience of local communities. Short supply chains also strengthen the link between producers and consumers, thus encouraging the adoption of more responsible production and consumption patterns (Mbow et al. 2019). Overall, promoting re-localized food systems could help not only contribute to climate change mitigation and adaptation but also address many other SDGs.

---

[18] For instance, imported open-field tomatoes can emit much less GHGs than local tomatoes produced in heated greenhouses (Theurl et al. 2014).

3 Improve waste management

3.1 Reduce food losses and waste along food value chains

According to an often-quoted estimation, global food losses and waste (FLW)[19] represented in 2007 globally about 1.3 Gt,[20] that is one quarter to one-third of all food produced for human consumption (FAO 2011a, 2013b; HLPE 2014; Porter et al. 2016; Guo et al. 2020). FLW have tripled between 1960 and 2011 (Porter et al. 2016), following both the population growth and the increase in average FLW per capita[21]. They account for 8-10% of total anthropogenic emissions,[22] i.e. 4 – 5 GtCO2eq per year, making it the third top GHG emitter just after China and USA (FAO 2013b, 2015; Mbow et al. 2019). They represent 38% of the energy consumed in food systems and 10% of the energy consumed in the world (FAO 2017). They consume 23% of all the fertilizers globally used on food crops, producing additional GHG emissions, and pollution of soils and water bodies (Kummu et al. 2012). They generate a land footprint of about 1.4 billion ha, equivalent to the current global cropland area, mainly driven by meat and milk products,[23] and a blue water footprint of 250 km^{3,} mainly driven by cereals and pulses,[24] higher than the blue water footprint of any country (FAO 2013b) and equivalent to 6% of global economy-wide annual freshwater withdrawals.[25] Food crops lost and wasted represent 24% of total freshwater consumed by food crop production (Kummu et al. 2012). FLW entail a direct economic cost of about USD 1 trillion each year (Mbow et al. 2019), equivalent to 25% of the world agricultural gross production value,[26] as well as huge social and environmental externalities estimated respectively at USD 900 and 700 billion per year (FAO 2014). In developed countries, FLW occur mainly at the consumption stage, due to unsustainable consumer preferences and behaviors. Whereas in developing countries, poor equipment and infrastructures explain why most FLW occurs earlier in the value chain, during food harvesting, processing, storage and transport (HLPE 2014; Porter et al. 2016; Niles et al. 2018; Mbow et al. 2019; FAO 2011a, 2013b, 2017, 2019).

Following population and income growth, the demand for agricultural products is expected to grow by 35 – 50% between 2012 and 2050,

---

[19] "Food loss and waste (FLW) refers to a decrease, at all stages of the food chain from harvest to consumption in mass, of food that was originally intended for human consumption, regardless of the cause" (HLPE 2014).

[20] This figure covers only the edible part of FLW. Including also the non-edible part, the total amount of FLW reaches 1.6 Gt according to FAO (2013b) and Porter et al. (2016) and 1.9 Gt according to Guo et al. (2020).

[21] Using the figures given by Porter et al. (2016) for the global amount of FLW (in mass) and by FAOSTAT for global population, one can show that global average annual FLW per capita grew from 175 to 230 kg between 1961 and 2011.

[22] Cereals and pulses represent more than 60% of GHG emissions from FLW (FAO 2019).

[23] FAO (2013b) affirmed that meat and milk account for 78% of this land footprint but for only 11% of global FLW. In a more recent publication, FAO (2019) considers that animal products explain 60% of the land footprint associated with FLW.

[24] According to FAO (2019), cereals and pulses contribute over 70% of the water footprint associated with FLW, followed by fruits and vegetables.

[25] In 2019, total freshwater withdrawals reached 3,963 km^3. See the corresponding World Development Indicator, developed by the World Bank based on FAO AQUASTAT data: https://data.worldbank.org/indicator/ER.H2O.FWTL.K3

[26] That is USD 4.1 trillion in 2020. See FAOSTAT: https://www.fao.org/faostat/en/#data/QV (accessed 6 February 2023).

increasing the pressure on natural resources and highlighting the importance of urgently reducing FLW (FAO 2017, 2019). In a world where the number of hungry people reaches 768 million people [range: 702-828] and follows an increasing trend, FLW represent a huge and unacceptable wastage of natural resources (FAO 2017; FAO/IFAD/UNICEF/WFP/WHO 2022). They threaten climate change mitigation and adaptation and aggravate food and water insecurity, pollution, land degradation and biodiversity loss. Hence, reducing FLW is one of the most effective no-regret win-win option to mitigate climate change while addressing many other SDGs (FAO 2019; Babiker et al. 2022).

Reducing FLW holds a global mitigation potential estimated at 0.76–4.5 GtCO2eq per year (Roe et al. 2019). Reducing FLW could also contribute to free up to 7 million km2 of land that, appropriately restored and sustainably managed could provide multiple co-benefits for food and water security, climate change and biodiversity (Smith et al., 2020).

FLW reduction will occur through changes in consumer preferences and behaviors and, on the supply-side, through technical solutions (such as improved harvesting, processing and packaging techniques, improved storage and transport infrastructure), or through political or market-based solutions (such as taxes,[27] incentives, regulations, voluntary standards, active marketing of cosmetically imperfect products or a higher variety of portion sizes) (HLPE 2014; Mbow et al. 2019; Nabuurs et al. 2022; Babiker et al. 2022). In particular, improved packaging, including active, smart and intelligent packaging, is crucial in FLW reduction as it contributes to extend the product shelf-life, prevent damages during transport and handling, enable easy opening and emptying, preserve food quality and safety and inform consumers about food storage and preparation (Molina-Besch et al. 2019; Babiker et al. 2022). A trade-off appears here because of the GHG emissions and plastic waste generated by packaging manufacturing and disposal (FAO 2019; Babiker et al. 2022). However, the IPCC (Babiker et al. 2022) evaluates that packaging (mainly pulp and paper and aluminium) generates about 0.98 GtCO2eq per year, that is around 6% of total food system emissions only, which suggests that benefits from improved packaging should generally outweigh GHG emissions associated with packaging itself. The ecological footprint of packaging can be further limited by reducing the volume of unnecessary packaging (e.g. through the development of bulk sales),[28] shifting away from fossil-fuel derived packaging and using sustainable and renewable and reusable materials (Coelho et al. 2020).

Totally eliminating FLW might not be feasible. Some losses are unavoidable along food value chains, for technical or economic reasons, and spoiled food must be discarded to ensure food safety. Eliminating FLW might not even be desirable as some margins of overproduction are needed as a safety net to ensure availability and stability of the food supply (HLPE 2014; Mbow et al., 2019; FAO 2019). Yet, FLW can be substantially reduced and the 2030 Agenda for Sustainable Development (UN 2015) suggests to "halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses" by 2030 (SDG 12.3). According to Kummu et al. (2012), halving global FLW would suffice to feed one additional billion people. Current estimates of FLW are of the same magnitude as the additional food quantity required to meet the increasing global demand in 2050 (FAO 2013b; Porter et al. 2016). Hence, eliminating hunger and malnutrition is no longer mainly a food production issue, requiring further agriculture expansion and intensification, but rather a distributional issue that can be addressed while alleviating the pressure on land, water and natural resources (IPES-Food 2016; HLPE 2014, 2017, 2019; FAO 2013b, 2017; Babiker et al. 2022). Incentives and regulations can facilitate the safe distribution of unavoidable FLW to poor population groups, and encourage waste reuse and valorization through different methods (see next section) (Mbow et al. 2019).

---

[27] e.g. "pay as you throw (PAYT)" tax mechanisms for household waste. See for instance: https://greenbestpractice.jrc.ec.europa.eu/node/7

[28] In particular, Poore and Nemecek (2018) found high proportions of GHG emissions from packaging for beverages and for some fruits and vegetables.

3.2 Improve waste management and valorization

Reducing FLW not only reduces GHG emissions and impacts on natural resources generated across the different stages of the food supply chain but also those generated during waste management and disposal (HLPE 2014; FAO 2019). The latest IPCC assessment report (Babiker et al. 2022) estimates that management of waste from the food system (including food waste, packaging waste, wastewater) emitted overall 1.7 GtCO2eq in 2018 (mainly CH4 and N2O), distributed as follows: domestic and commercial wastewater (55%), solid waste (36%) and industrial wastewater (8%). The remaining 1% comes from waste incineration and other waste management systems. Waste management is generally the second source of GHG emissions in cities, after the energy sector. Hence, municipal waste management systems should be one of the main targets of mitigation strategies at the level of cities and urban areas. Such strategies should try also to minimize waste transport and associated emissions through compact urban forms, distributed waste management facilities, or home composting (Lwasa et al. 2022). In developing countries, the waste management sector is still largely informal. With proper regulations and incentives, this sector could become an important source of economic growth: it could generate 45 million additional jobs until 2030 (Lwasa et al. 2022).

Organic waste from the food system can be reused and valorized through different methods. Anaerobic digestion of organic waste, whether solid or liquid (e.g. food waste, manure, domestic and municipal organic waste, wastewater) produces biogas (mainly CH4) that can be used as an energy source for cooking, or heat or power generation, as well as a digestate rich in nitrogen, phosphorus, carbon and other plant nutrients that can be applied on agricultural lands. The risk of contamination from pathogens is lower after the anaerobic digestion process than in undigested manure, even if all pathogens may not be destroyed. Depending on the quality of the original feedstock, there is also a risk for the digestate to be contaminated by heavy metals (such as manganese, copper and zinc) (Mbow et al. 2019; Babiker et al. 2022). Through pyrolysis, organic waste (including food waste, manure, litter and sewage sludge, agricultural and forestry residues) can be transformed into biogas for cooking or energy and into biochar returned as amendment to agricultural soils (see Section 10.2). Conversion of organic waste into biochar reduces mass and odors, improves stability and uniformity and, hence, facilitates handling, storage, transport and application to soils. However, a large share of nitrogen is lost to the atmosphere during this process. Pyrolysis is also a way to reduce or remove contamination by heavy metals, pathogens, microplastics or other toxic substances that are destroyed or eliminated during the process (Joseph et al. 2021; Babiker et al. 2022). Organic waste can also be used as insect feed or for the production of fungi or of microbial protein (Pikaar et al. 2018; Mbow et al. 2019). The development of second generation biorefineries will facilitate the transformation of organic waste into biofuel, bioenergy, bioplastics or other biochemicals to reduce our dependence to fossil fuels and provide complementary sources of income (Mbow et al. 2019).

4 Improve energy use across food value chains

4.1 Develop clean and renewable energy

Future bioenergy production is constrained mainly by land availability and productivity (Jia et al. 2019). The IPCC (2018) found that the 1.5°C target cannot be reached without significant bioenergy deployment. All 1.5°C consistent pathways imply a production of bioenergy of about 150 EJ per year [full range: 40 – 310 EJ]. The total technical mitigation potential of bioenergy with carbon capture and storage falls in the range of 0.4–11.3 GtCO2 per year till 2050 (Roe et al. 2019), without accounting for the avoided emissions associated with the substituted fossil energy systems (Babiker et al. 2022). Yet, based on previous studies, the IPCC (2018) evaluated that the sustainable bioenergy production potential in 2050 could rather be limited to around 100 EJ per year, equivalent to a sustainable mitigation potential of 2 – 5 GtCO2 per year and representing 62 – 290 million ha of land dedicated to energy crops.[29] This is of the same order of magnitude than the economic potential of 0.5 – 3.5 GtCO2 per year estimated by Nabuurs et al. (2022) at carbon prices below USD 100 per tCO2.[30]

In 1.5°C consistent pathways, up to 7 million km^2 need to be dedicated to energy crops by 2050 (IPCC 2018), i.e. almost half of the current global crop land area. Estimates of marginal or degraded lands that could be used for bioenergy production fall in the range of 3.2 – 14 million km2 (Jia et al. 2019), although what constitutes a marginal and degraded land and how much land is available and suitable for bioenergy production are still debated questions (HLPE 2013, Smith et al. 2014). However, bioenergy deployment at such levels may seem unreachable as they would involve large direct and indirect land use changes, increasing dramatically the competition for land, water and natural resources, causing disruptive impacts on food and feed production and food prices, and threatening biodiversity, food and water security and livelihoods.

The carbon, land and water footprints of bioenergy, as well as its socio-economic impacts, are highly context-specific. They depend not only on the scale and pace of their deployment but also on local soil and climate conditions; on the socio-economic and institutional context; on prior land-use and soil carbon stock; on land management practices (in particular nutrient management); on crop yields; on the efficiency of biomass processing and transport; on costs, prices and related incentives (HLPE 2013; Smith et al. 2014; Hoegh-Guldberg et al. 2018; de Coninck et al. 2018; Jia et al. 2019; Olsson et al. 2019). Estimated yields for dedicated energy crops for instance can vary from 1 to over 10, depending on soil, climate, land management, feedstock and conversion process, leading to huge variations in the estimated land demand for bioenergy across climate scenarios (Smith et al. 2014).

Bioenergy's ecological footprint also depends on the feedstock used (dedicated energy crops vs. crop residues or by-products) and its complementarity or competition with feed, food or wood production. Dedicated energy crops generally produce higher yields (in EJ per ha), which mean a lower land requirement (in Mha per GtCO2 removed). Smith et al. (2015) evaluated the land

---

[29] Using for bioenergy with carbon capture and storage the following conversion factors: 0.02 – 0.05 GtCO2 removed per EJ of bioenergy produced and 31 – 58 Mha per GtCO2 removed (Smith et al. 2015; Hoegh-Guldberg et al. 2018).

[30] This potential includes direct emissions and removals from land use changes and bioenergy production but does not consider avoided emissions associated with energy carrier substituted by bioenergy which, following IPCC guidelines, are not accounted for in the AFOLU sector.

demand for dedicated energy crops, agricultural residues and forest residues respectively at: 30 – 100 Mha per GtCO2, 160 Mha per GtCO2 and 300 – 500 Mha per GtCO2 removed. However, when considering the whole life-cycle, biomass from dedicated crops also generate higher GHG emissions (in GtCO2 per EJ produced) than agriculture or forest residues and can increase sensibly the competition with food and feed production for land, water and nutrients (de Coninck et al. 2018; Jia et al. 2019). If judiciously integrated in farming systems,[31] perennial energy crops, such as Miscanthus or short rotation woody crops, can provide multiple environmental benefits, including erosion control, prevention of nutrient leaching, shade or shelter for animals, pollination, pest and disease control, soil carbon sequestration, flood regulation or resorption of water pollution. They can thus contribute to the restoration of marginal or degraded lands. On the other hand, bioenergy from agricultural and forest residues or by-products can be better integrated in farming and forestry systems with no or limited competition with food, feed and wood production. Yet, the bioenergy production and mitigation potentials from residues remains limited,[32] and removing residues from the soil can, over time, accelerate land degradation. (Smith et al. 2014; Jia et al. 2019; Babiker et al. 2022).

This diversity of situations and the complex trade-offs involved explain why the opportunity and sustainability of large-scale deployment of bioenergy production is still subject to debate and gives rise to strong oppositions. For instance, some studies affirmed that biofuel deployment and other land-based mitigation efforts could have more disruptive impacts for crop prices, land use and land use changes than climate change alone (Ruane et al. 2018; Hasegawa et al. 2018). By contrast, Lotze-Campen et al. (2013) highlighted that bioenergy deployment could have little impacts on food prices or food availability if the bioenergy feedstock is grown on marginal land or does not compete with food production, like in the case of lignocellulosic bioenergy.

Beyond bioenergy, other forms of clean and renewable energy (e.g. wind or solar power, hydroelectricity or geothermal sources) are already applied and can be further developed on farm and throughout food supply chains (Mbow et al. 2019).

4.2 Improve energy-use efficiency across food value chains

According to Smith et al. (2020), improved energy use in food systems could save about 0.37 GtCO2eq per year. But this estimation seems quite low. Focusing only on cleaner cookstoves, Roe et al. (2019) found that improving combustion efficiency could save up to 0.81 GtCO2eq per year, which suggests that the total potential of energy savings across food value chains could be much higher. The corresponding global cost-effective potential, available at carbon prices below USD 100 per tCO2, has been evaluated globally at 106 MtCO2eq per year (Roe et al. 2021).

At the production stage, conservation tillage, precision farming and other sustainable farming practices can contribute to improve resource-use efficiency, reduce on-farm energy-use and associated GHG emissions (Mbow et al. 2019).

Important mitigation potentials could be realized during food transport through improved logistics, reduced food miles, alternative fuels and transport modes (Babiker et al. 2022; Jaramillo et al. 2022). According to FAOSTAT, food transport is globally responsible of 3.3% of total food system emissions (see Table 2 above). This is in line with the latest IPCC estimation which evaluates food transport at about 5 – 6% of total food system emissions (Babiker et al. 2022). Although transport represents a marginal share of the carbon footprint for the majority of food products, it can become important for foodstuffs with high water content and low farmgate emissions, transported over long distance (Babiker et al. 2022). For instance, for bananas, transport is responsible of over 40% of total GHG emissions by kg of product (Poore and Nemecek 2018). The type of fuel used and the mode of transport chosen have profound impacts on energy consumption and associated emissions (Babiker et al. 2022). Brodt et al. (2007) found that, with the same quantity of fuel, 5 kg of food can be transported over 1 km

---

[31] Within crop rotation or strategically localized, e.g. as riparian buffers, contour belts or along fence lines.

[32] The bioenergy production potentials from residues vs. dedicated energy crops have been evaluated at 4 – 57 and 46 – 245 EJ per year respectively by 2050 (Nabuurs et al. 2022).

by personal car, 43 km by airplane, 740 km by truck, 2,400 km by rail, and 3,800 km by ship.[33] According to the IPCC, road concentrates 92% of food transport emissions, while the shares of other mode remains marginal with 4% for marine shipping, 3% for railway, and 1% for air transport (Babiker et al. 2022). Using a simple global food transport model, Kriewald et al. (2019) found that reducing the number of food miles by harnessing the potential of peri-urban agriculture could divide GHG emissions from food transport by a factor 10. Promotion of active transport modes (walk, bicycle) for food distribution on the last km can reduce GHG emissions, as well as traffic congestion, while providing further co-benefits for human health and air quality (Lwasa et al. 2022). Improved logistics, including improved packing densities in transport vehicles can also reduce the need for food transport and associated GHG emissions (Babiker et al. 2022).

Food processing can extend shelf-life, enhance food safety and increase palatability, desirability or nutritious value of foods, reduce FLW, increase dietary diversity all year long (Niles et al. 2018). However, food processing is responsible of almost 3% of global food system emissions (FAOSTAT, see Table 2 above). As such, it is another area of attention for climate change mitigation beyond farmgate. Energy-intensive processes such as milling, refining, sterilization and pasteurization should be targeted to track potential energy savings (Niles et al. 2018). Wang (2013) found for instance that the British food processing industry could save 25 – 34% of energy consumed by applying the best existing and economically viable technical options. Low-carbon energy sources or processes should be encouraged, including ambient cooling, sun drying or food smoking (Babiker et al. 2022). Fritzson and Berntsson (2006) estimated that CO2 emissions in the slaughter and meat processing industry could be reduced by 5 – 35% through investments in heat pumps or heat exchanger networks. Using combined heat and power facilities in food processing is another avenue for energy savings (Fischedick et al. 2014).

4.3 Improve urban form, spatial urban planning and develop urban agriculture

Since 2007, more than half of the world's population is urban (UNDESA 2019). The world's share of urban population is expected to increase from 55% in 2018 to 68% in 2050, adding about 2.5 billion urban dwellers to the world population, of which almost 90% should occur in Asia and Africa (UNDESA 2019; Lwasa et al. 2022). Although rapidly expanding, human infrastructure (including human settlements, industrial sites, roads and rails) still covers a marginal share, about 7%, of total land area (Hooke and Martín-Duque 2012; Pesaresi et al. 2016). Within urban areas, built-up areas (i.e. sealed soils and buildings) cover just about 0.4 – 0.9% of global land area (IPBES 2018; Jia et al. 2019). But they have a disproportionate impact on the economy, on climate change and the environment. Urban centers consume 70% of the food produced (FAO 2018b) and account for 60% of residential water use (Grimm et al. 2008), 67 – 76% of global energy use (Seto et al. 2014) and 67–72% of global GHG emissions – i.e. 29 GtCO2-eq in 2020[34] (Lwasa et al. 2022). They concentrate 80% of the jobs (WB/FAO 2017) and 80% of the global gross domestic product (Grübler and Fisk, 2013). As such, cities are central places for effective and impactful food system governance and mitigation actions addressing urban form[35]. The growing concentration of people and activities in cities is a huge opportunity for innovation, improved resource-efficiency and decarbonization at scale (Mbow et al. 2019; Lwasa et al. 2022; Babiker et al. 2022).

The number and size of urban settlements is expected to grow in the coming decades to accommodate the growing urban population.

---

[33] On the same note, FAO (2011b) ranked the different transport modes according to their energy consumption per ton and km. They found: 8 – 10 MJ per ton and km for transport by rail, 10 – 20 MJ by marine shipping,70 – 80 MJ by road and 100 – 200 MJ by airplane. The following emissions factors have been used in modelling exercises: 680 gCO2 per ton and km for air food transport, 120 gCO2 for terrestrial food transport and 13.5 gCO2 for maritime food transport (Cristea et al. 2013; Kriewald et al. 2019)

[34] Including both direct urban emissions and indirect emissions driven by urban centers outside urban areas.

[35] The concept of "urban form" refers to the form of the physical environment in urban areas. It encompasses all the physical characteristics, including for instance size and density of human settlements. It considers the design, extent and spatial configuration of buildings (for different uses), transportation networks and other infrastructure (Lynch and Rodwin 1958; Lwasa 2022).

Urban land area could triple between 2015 and 2050 (Seto et al. 2012; Lwasa et al. 2022). In other words, before mid-century more urban infrastructure could be built than what currently exists. This is an unprecedented opportunity to further climate change mitigation and adaptation and other SDGs by building sustainable cities and limit unsustainable carbon lock-ins (Seto et al. 2014, 2016). Designing sustainable and climate-smart cities today is far easier than retrofitting and upgrading established cities already locked in unsustainable development pathways (Seto et al. 2016; Lwasa et al. 2022). However, 95% of the expected increase in urban population should take place in less developed countries (UNDESA 2019). Hence, the greatest opportunities appear where institutional, financial, and technical capacities to realize them are the weakest (Seto et al. 2014; UNDESA 2019), which creates what has been called the "governance paradox" (Grubler et al. 2012) that would need to be addressed to realize this emission reduction potential.

Because of the long lifetime of buildings,[36] roads and other infrastructure, unsustainable urbanization would lock-in energy consumption patterns and associated GHG emissions for decades or generations (Seto et al. 2014; Seto et al. 2016; IPCC 2018; Lwasa et al. 2022). Davis et al. (2010) calculated for instance that committed cumulative emissions from existing energy and transport infrastructure could reach 496 GtCO2 (range: 282-701 GtCO2) between 2010 and 2060 and generate a global mean warming of 1.3°C (range: 1.1 - 1.4°C), leaving very narrow margins to achieve the Paris Agreement targets.[37] Future urban forms and urban planning strategies will determine urban energy consumption and GHG emissions for the decades to come. They will shape cities' vulnerability to climate change, adaptive capacities and contribution to climate change mitigation (Seto et al. 2014; Creutzig et al. 2016; de Coninck et al. 2018; Lwasa et al. 2022).

Four characteristics of urban form must be considered in effective spatial urban planning strategies as critical drivers of urban energy use and GHG emissions: (i) high urban density; (ii) high land-use mix, co-locating in the same area housing, job opportunities and commerce; (iii) high street connectivity, linked to the size of building blocks; and (iv) high accessibility allowed by transit-oriented development[38] (Seto et al. 2014; Seto et al. 2016; Lwasa et al. 2022). Such compact and walkable urban forms, which privilege active or public transport modes over private motor vehicles and reduce the distance between house, office and leisure activities, could reduce urban energy consumption and GHG emissions from urban transport by 20 – 50% and hold a mitigation potential of 23 – 26% by 2050 (Seto et al. 2014; Creutzig 2016; Lwasa et al. 2022). Higher urban densities could also spare lands for urban and peri-urban agriculture or urban green infrastructure that can contribute to strengthen food security and nutrition, regulate local climate, reduce the urban heat island effect, improve water infiltration and prevent flooding and increase soil carbon sequestration (Jia et al. 2019; Mbow et al. 2019; Olsson et al. 2019). Tsilini et al. (2015) for instance found that urban gardens have the potential to reduce surface temperature by up to 10°C when compared with non-vegetated soils.

Nowadays, 40% of the world's cropland area, including 60% of all irrigated cropland, are situated in peri-urban areas, i.e., within 20km of cities (Thebo et al. 2014). The remaining peri-urban agricultural lands, which are often among the most productive since many cities historically developed on fertile alluvial plains, are put under high pressure by the current dominant model of urban growth. In this dominant model, often called "urban sprawl" or "outward expansion", urban areas are growing twice as fast as the urban population (Angel et al. 2011; UNDESA 2019; Jia et al. 2019; Lwasa et al. 2022). Urban sprawl could displace 65 Mt of crop production between 2000 and 2040 (van Vliet et al. 2017) and consume 1.8-2.4% of current cultivated land by 2030 and up to 5% by 2050 (Jia et al. 2019) with serious implications for food security and soil carbon

---

[36] The lifetime of buildings varies considerably across contexts, depending on local conditions, design and materials used but, typically, span from 30 to over 100 years (Lwasa et al. 2022).

[37] This estimation does not consider GHG emissions associated with the production of materials needed to build new infrastructures, which could generate an additional 470 GtCO2 (Seto et al. 2014). More recently, Bai et al. (2018) estimated that urban development could generate 226 GtCO2 by 2050.

[38] i.e. develop compact, mixed and walkable urban environment, at a walking distance of a transit station of the public transport network.

sequestration in peri-urban agricultural, forested and semi-natural ecosystems (Lwasa et al. 2022).

However, as impervious surfaces cover only around 15% of total urban areas on global average (Liu et al. 2014), this leaves a lot of space for preservation and sustainable management of urban and peri-urban agricultural land, urban green infrastructure and semi-natural ecosystems if urban densification[39] is privileged over urban sprawl (Jia et al. 2019; Lwasa et al. 2022). Kriewald et al. (2019) estimated that, by harnessing the global potential of peri-urban agriculture, about one billion urban dwellers, that is 25 – 30% of global urban population, could be fed with local products. More innovative forms of urban agriculture, such as rooftop gardens, vertical farming or controlled-environment agriculture (e.g. hydroponic or aquaponic systems) can contribute to get the most of available spaces in urban areas, of available spaces in urban areas, privileging short growth-period, fresh, and high-value food products like vegetables (Kriewald et al. 2019; Lwasa et al 2022; Babiker et al. 2022). Urban and peri-urban agriculture, by reducing food miles, recycling organic waste and wastewater and providing a diversity of fresh and local foods could do a lot to reduce GHG emissions linked to food processing, transport, storage and waste management, adapt to climate change impacts, improve dietary quality and diversity provide additional job and income opportunities, enhance local agrobiodiversity and associated ecosystem services and support local soil carbon sequestration (Kriewald et al. 2019; Mbow et al. 2019; Lwasa et al. 2022).

---

[39] Lwasa et al. (2022) identify two modes of urban densification, which do not consume additional land: (i) “upward” vertical urban expansion, as opposed to “outward” horizontal expansion, and (ii) “infill” development where abandoned or under-utilised urban areas are developed or rehabilitated.

5 Optimize cold-chain efficiency in food systems

The cold chain represents about 1% of global CO2 emissions. However, this share should grow in the future since, globally, less than 10% of perishable food products are being refrigerated and since the volume of refrigerators per capita is ten times lower in developing countries than in developed countries (respectively: 19 and 200 m^3 per capita) (James and James 2010). Future warming will also increase the consumption of energy for refrigeration, and the associated CO2 emissions: a rise in ambient temperature from 24° to 32°C can increase energy consumption in the cold chain by 40% (James and James 2010).

GHG emissions from the cold chain originate from two main sources. First is energy consumption: The refrigeration system is responsible of 43% of energy consumption in the retail sector (Behfar et al. 2018), and of up to 40% of the diesel consumed during refrigerated food transport (Tassou et al. 2008). Second, direct GHG release: the manufacture and direct leakage of refrigerant gases cause significant emissions. According to the IPCC, the refrigerant industry emits 580 MtCO2eq per year as fluorinated gases (Babiker et al. 2022). European experts estimated that refrigerant leakage is responsible for around 20% of the global warming impact of refrigeration plants (March Consulting Group, 1998). Over the past decades, the refrigeration system has mainly used as refrigerants fluorinated gases such as chlorofluorocarbons (CFCs) or hydrochlorofluorocarbons (HCFCs). These gases, responsible for the ozone layer depletion, have been largely phased out under the Montreal Protocol. They have been replaced by other substances like hydrofluorocarbons (HFCs). However, like CFCs and HCFCs, HFCs have very high global warming power (thousands of times more than CO2) and recent changes in the Montreal Protocol require their elimination over the next 30 years[40] (James and James 2010; Niles et al. 2018).

Hence, two categories of mitigation options emerge to address these two sources of GHG emissions. First, energy consumption in the refrigeration system can be reduced by: proper maintenance of existing facilities (e.g. repairing and closing doors well, cleaning condensers); investment to replace current facilities by the best available ones (this way, energy consumption could be divided to 1/5–1/6 of the current values); or better design of refrigeration facilities and exploration of innovative refrigeration methods.[41] Adapting storage temperature in refrigeration systems more precisely to the different food products, through advanced temperature control systems, and relying more on initial ambient cooling in food preparation can sensibly reduce energy consumption without threatening food safety and quality. Improved packaging and product conservation may also increase shelf-life and allow the use of higher storage temperature in the cold chain (James and James 2010; Babiker et al. 2022).

Second, the use of alternative refrigerants with lower global warming power can be encouraged – it is currently already explored – to replace fluorinated gases in refrigeration systems.

---

[40] Kigali amendment to the Montreal protocol (2016). For more information, see for instance: https://wedocs.unep.org/bitstream/handle/20.500.11822/26589/HFC_Phasedown_EN.pdf

[41] Such as: "trigeneration, air cycle, sorption – adsorption systems, thermoelectric, thermoacoustic and magnetic refrigeration", as well as "solar-powered, hydrogen or geothermal refrigeration" (Tassou et al. 2009; James and James 2010).

Alternatives include ammonia, propane, isobutane, carbon dioxide, water and air. Ammonia, which is not a GHG, is commonly used in large industrial refrigeration and storage plants as a cheap and efficient refrigerant. Its pungent odor facilitates leak detection before reaching toxic levels or flammable concentrations (James and James 2010; McLinden et al. 2017).

There is a trade-off between reducing FLW, and associated GHG emissions and ecological footprint on one hand, and increasing emissions from the cold chain on the other hand (FAO 2019). For instance, the International Institute of Refrigeration (IIR 2009) found that, with the same level of refrigeration facilities than in developed countries, over 200 million tons of perishable foods could be preserved in developing countries, i.e. about 14% of current consumption, with important impacts on food security, poverty reduction and the environment in these countries. If cold chain development is properly combined with improved energy-use efficiency, GHG emissions saved through food waste reduction could outweigh increased emissions from the cold chain with substantial co-benefits for food security, food safety, dietary diversity and poverty reduction (James and James 2010, Niles et al. 2018; FAO 2019). However, cold chain extension can also facilitate access to GHG intensive products such as meat, processed food or non-seasonal food, or encourage excess buying of food products. Hence, if cold chain extension is not combined with education to sustainable consumption patterns, it could accelerate the shift towards GHG intensive and unhealthy diets (Heard and Miller 2016).

6 Reduce emissions from enteric fermentation

As illustrated in Table 2, enteric fermentation is, by far, the main source of farmgate GHG emissions. These emissions depend both on ruminant livestock numbers and productivity (output per animal). As shown in Section 2.1, ruminant livestock populations in the decades to come will be determined mainly by the demand for meat, milk and derived products. In turn this growing demand will be driven by population and income growth and changes in diets. However, for a given level of livestock population, it is still possible to reduce CH4 emissions intensity, i.e. emissions by animal or by unit of product (Mbow et al. 2019; Nabuurs et al. 2022).

At the animal level, several strategies exist to reduce the intensity of CH4 emissions from enteric fermentation and manure excretion, for instance: shift to lower-emitting livestock species, better adapted to their environment; improve grazing management;[42] increase forage digestibility[43] including through feed processing; improve animal diets (with e.g. dietary lipids, concentrate feeds, legumes and other high-protein feeds); introduce supplements and additives (e.g. plant bioactive compounds such as tannins, saponins and essential oils or direct-fed microbials such as yeast-based products); improve feeding management practices (e.g. total mixed rations, precision feeding and feed analyses) (Hristov et al. 2013; Mbow et al. 2019; Nabuurs et al. 2022). According to the latest IPCC assessment (Nabuurs et al. 2022), introducing appropriate amounts of biochar in ruminant diets could help reducing enteric CH4 emissions.

However, transition to improved animal diets can create trade-offs. For instance, Grainger et al. (2009) found that tannins can reduce CH4 emissions (by up to 30%) and urinary N losses from grazing dairy cows but also affect diet digestibility and nutritional value, thus reducing milk production by about 10%. Dietary lipids may mitigate CH4 emissions but also limit dry matter intake thus lowering animal productivity (Hristov et al. 2013). Diets higher in grains shall decrease CH4 emissions (due to lower roughage intake) but increase CO2 and N2O emissions associated with the production of feed crops (energy, fertilizers and land use changes), which persist in the atmosphere for longer periods. As a result, the quantified benefits of a given strategy will depend on assumptions made for the CH4 GWP at short- and long-term time horizon (Mbow et al. 2019). Increased feed crop production could also have wider negative impacts on the environment (conversion of natural ecosystems, pollution of soils and water).

Improving animal health is another way to reduce significantly average emission intensity (per animal) by improving animal productivity and fertility and reducing the burden of diseases and premature mortality. Fewer but better-fed and more productive animals can produce the same benefit for food security with less GHG emissions, in particular in developing countries (Mbow et al. 2019).

More innovative technologies, not yet economically feasible at scale, are being explored, including: methane and nitrification inhibitors, electron receptors, exogenous enzymes; manipulation of rumen microflora through early life interventions or by inoculating fungi, direct-fed microbials or

---

[42] Intensive grazing is generally considered to improve feed efficiency, resulting in increased milk and meat productivity and reduced CH4 emission intensity (DeRamus et al. 2003, Hristov et al. 2013).

[43] Forage digestibility is determined among others by forage composition and grass maturity at harvest time (Hristov et al. 2013). For instance, Archimède et al. (2011) found that C4 grasses in ruminant ration produce 17% more CH4 per kg of organic matter intake than C3 grasses and 20% more than warm climate legumes.

methane vaccines; genetically modified grasses and feed crops; as well as novel feedstocks such as macroalgae, seaweeds, insects or microbial protein (Hristov et al. 2013; Pikaar et al. 2018; Mbow et al. 2019; Nabuurs et al. 2022). For instance, tests on a well-known anti-methanogenic agent, called 3-nitrooxypropanol (3-NOP), demonstrated its potential to decrease CH_4 emissions by up to 40 - 60% when introduced in ruminant diets (Hristov et al. 2013, 2015). However, as the rumen ecosystem adapts, these inhibitors have uncertain effects in the long-term and concerns remain about their palability, toxicity and environmental impacts (Hristov et al. 2013; Nabuurs et al. 2022).

Overall, the global mitigation potential of such activities reducing the intensity of emissions from enteric fermentation is evaluated at 0.12-1.18 $GtCO_2eq$ per year (Roe et al. 2019), of which 0.1 – 0.3 could be available at carbon prices below USD 100 per tCO_2eq (Nabuurs et al. 2022).

7 Optimize manure management

Animal manure contains most if not all of the essential elements required for plant growth[44] (including C, N, P). It can substitute expensive, energy- and GHG emission-intensive synthetic fertilizers while providing a range of co-benefits for ecosystems and livelihoods. Adequate application of animal manure to croplands increases soil organic matter, microbial biomass and mineralization rate. It improves soil structure and properties, reducing soil erosion and nutrient leaching and increasing oxygen content and water-holding capacity, thus improving soil fertility and crop yields (Montes et al. 2013).

CH4 emissions from manure management occur mainly during manure storage under anaerobic conditions while N2O emissions mostly follow land application as a byproduct of microbial (aerobic) nitrification and (anaerobic) denitrification processes in soils. These complex processes, which depend on manure composition, temperature, soil microbial population, moisture content and oxidation status, as well as on availability of easily degradable organic carbon, make N2O emissions and corresponding mitigation potentials highly variable and their estimation challenging. In addition, a significant proportion (up to 50 - 60%) of the excreted N is rapidly lost through volatilization within a few days after excretion. The excreted N volatilizes mainly as NH3[45] (for 30 – 70% of NH4$^+$ content of cattle manure), but also in the form of N2O, NO, NO2 or N2 (van Horn 1998; Montes et al. 2013).

Reducing the demand for animal products and thus monogastric and ruminant livestock populations is the first way to reduce emissions from manure excretion. However, for a given population of living animals, the intensity of CH4 and N2O emissions from manure can be further reduced by a range of measures including: improved grazing practices (e.g. shifting livestock pens for a more uniform distribution of N left on pasture as urines or feces, optimizing grazing intensity and grazing periods to improve N uptake by plants); changes in livestock diet to reduce degradable organic carbon and excreted nitrogen (e.g. optimizing forage digestibility, crude protein, fiber and concentrate proportion in daily ration, feed additives); improved animal housing and manure management facilities (e.g. gases biofiltration in animal buildings, sealed manure storage, methanizers); improved manure storage management (e.g. reducing storage time, lowering storage temperature, aerating or acidifying manure, applying nitrification or urease inhibitors to manure or urine stocks, storage cover with straw, natural or induced crust, litter stacking); improved manure application to soils (e.g. application timing avoiding wet conditions, application method such as sub-surface injection, matching manure fertilization with plant requirements and soil nutrient balance, using cover crops); improved manure treatment and valorization (e.g. solids separation, anaerobic digestion, aerated composting, photocatalytic degradation, drying,

---

[44] Beyond carbon, oxygen and hydrogen, these include six macro-nutrients, needed in large quantities (nitrogen, phosphorous, potassium, calcium, magnesium and sulfur) as well as other micro-nutrients, needed in smaller quantities (e.g. manganese, copper, zinc, chlorine, boron, iron, molybdenum, as well as nickel, silicon, sodium, vanadium and cobalt).

[45] NH3 and NH4$^+$ are not GHGs but they enter the N cycle, feeding the nitrification and denitrification processes which generate N2O emissions; they impact air quality and contribute to acid deposition on soils and eutrophication of water bodies.

incineration, or thermal gasification) (Montes et al. 2013; Jia et al. 2019; Mbow et al. 2019).

These mitigation measures can create trade-offs. For instance, low-protein diets could reduce NH3 and N2O emissions but likely increase CH4 emissions and, if poorly formulated, impact animal productivity. Increasing pen cleaning frequency reduces N volatilization and, hence, increases the N content in manure, with the risk of increasing N2O emissions at later stages in case of poor manure management practices during storage, treatment and application to soils. Subsurface manure injection in soils reduces CH4 and NH3 emissions, leaving more N at risk of being emitted later as N2O through nitrification and denitrification processes. Aeration of manure during storage or composting, by preventing anaerobic conditions, can reduce CH4 emissions but increase NH3 and N2O emissions. However, adding mature compost with nitrite-oxidizing bacteria to swine manure during composting has the potential to reduce N2O emissions by about 70%. Manure storage with semipermeable cover can effectively reduce odors as well as CH4 and NH3 emissions, but likely increases N2O emissions. In intensive grazing systems, keeping animals off the paddocks in stand-off areas of feed pads during wet seasons not only reduces N2O emissions but also damages to pasture and soil compaction. On the other hand, this practice can sensibly increase N volatilization and NH3 emissions while mixed urines and feces remain on the stand-off or feed pad area (Montes et al. 2013).

Manure management options might not be easy to implement. First, they may entail important upfront costs to build the needed infrastructure (such as slurry tanks or anaerobic digesters). Second, they require adopting an integrated system thinking, considering different driving forces, combining different practices and managing efficiently the trade-offs that may appear between N2O, CH4 and NH3 emissions or among different stages of the manure management process (Montes et al. 2013; Mbow et al. 2019). Hence, manure management options are easier to apply in intensive and confined systems, where important quantities of manure can be more easily collected and valorized (Jia et al. 2019; Mbow et al. 2019). In developing countries, huge quantities of nutrients are commonly lost due to poor manure management practices. Tittonell et al. (2009) found for instance that poorly managed intensive ruminant livestock systems in Kenya can lose up to 70% of nitrogen within the six months following manure excretion. In many places, manure is still considered as a waste, left unused or discharged into water bodies, generating important water and air pollution, even in places with very limited nutrient (N and P) resources (Mbow et al. 2019).

Overall, Nabuurs et al. (2022) assessed, with medium confidence, a global mitigation potential for improved manure management reaching 0.1 – 0.5 GtCO2eq per year, out of which 0.09 – 0.1 GtCO2eq per year could be available at carbon prices below USD 100 per tCO2eq.

8 Reduce emissions from synthetic fertilizers manufacturing and application

The agricultural use of nitrogen fertilizers has been globally multiplied by almost 10 over the last decades (1961 – 2020),[46] driven by the search for higher yields to meet the needs for food, feed, fuel and fiber of a rapidly growing population. This entailed a similar increase in associated N2O emissions over the same period.[47] As said above, the demand for agricultural products is expected to further grow by 35 – 50% during the next decades until 2050 (FAO 2017, 2019). Should the use of nitrogen fertilizers increase in the same proportions, it could have dramatic impacts on N2O emissions, as well as on soil and water pollution. Yet, fertilizer use efficiency remains very low: important quantities of N are being lost through nitrate leaching, denitrification and ammonia volatilization. Mekonnen and Hoekstra (2015) evaluated the global nitrogen run-off at 35 million tons N per year, of which 70% (24.4 million tons per year) are coming from anthropogenic sources (i.e., organic and synthetic fertilizers). When compared to the global agricultural use of N fertilizers, [48] these figures highlight the promising potential of improved fertilizer management. These large losses confirm the idea, supported by many studies, that fertilizer use could be reduced by 30 to 50% without affecting crop yields (IPBES 2018). In its more extreme sustainability scenario for the Future of Food, FAO even suggests the progressive phasing-out of nitrogen mineral fertilizers until 2050 (FAO 2018a).

Since N2O emissions are a non-linear function of the N fertilization rate, moderated by soil characteristics and water availability, limiting excessive use of nitrogen would drastically reduce N2O emissions as well as soil, air and water pollution with no or limited impacts on yields. On the contrary, a judicious increase in fertilizer-use where current application rates are too low could make a huge difference for enhancing crop yields and food security and limiting further agriculture expansion, with limited increases in N2O emissions and limited collateral negative effects on the environment (Niles et al. 2018; Jia et al., 2019). Hence, national strategies and roadmaps for sustainable nutrient management are instrumental in identifying and scaling-up the policies, regulations and best practices most adapted to the national, sub-national and local context (Nabuurs et al. 2022). Limiting excessive use of fertilizer would not only reduce direct GHG emissions associated with fertilizer application, but also reduce indirect emissions associated with fertilizer manufacturing, the latter representing 62% of the former. In 2020, emissions from fertilizers manufacturing represented globally 389 MtCO2eq, of which 15% of N2O and 85% of CO2 linked to the energy used in the manufacturing process.[49]

Overall, Roe et al. (2019) found the following global mitigation potentials: 0.03 – 0.71 GtCO2eq per year for improved crop nutrient management (N2O) and 0.05–0.36 GtCO2eq per year for improved synthetic fertilizer production. The economic mitigation potential for improved crop nutrient management is estimated at 0.05 – 0.6 GtCO2eq per year for carbon prices below USD 100 per tCO2eq (Nabuurs et al. 2022). Improved crop nutrient management means optimizing fertilizer application following the 4R principle,

---

[46] From 11.5 to 113 million tons. See FAOSTAT: https://www.fao.org/faostat/en/#data/RFN (accessed on 6 February 2023).

[47] From 0.24 to 2.4 million tons N2O. See FAOSTAT: https://www.fao.org/faostat/en/#data/GT (accessed on 6 February 2023).

[48] 106.6 million tons in 2015. See FAOSTAT: http://www.fao.org/faostat/en/#data/RFN (accessed on 6 February 2023).

[49] See FAOSTAT, ibid.

i.e. ensuring that “the *Right* nutrient source is applied at the *Right* rate, in the *Right* place and at the *Right* time” (Smith et al. 2014; HLPE 2019; Fixen 2020; Nabuurs et al. 2022). This can be done by using precision technologies, slow- or controlled-release fertilizers, testing soils and adapting application rate, timing and fertilizer type to local soil and climate conditions and plant needs. Beyond individual practices, integrated crop nutrient management, building more upon biological processes, can improve nutrient flow and fertilizer-use efficiency in the whole farming system, including through: diversified crop rotations (including cover crops and legumes to fix atmospheric N and reduce leaching), reduced tillage, use of manure and organic fertilizers, incorporation of crop residues. Compared to conventional practices, evidence shows that organic agriculture could reduce energy consumption by up to 21% per unit of output and up to 70% per unit of land by eliminating the energy consumption associated with the manufacture and application of synthetic fertilizers (Meemken and Qaim 2018; Amenchwi et al. 2023). Mixed farming systems integrating crops, trees, livestock and fisheries (including rice-fish farming or agroforestry systems) can reduce dependance on external inputs (including synthetic fertilizers), and related costs, while improving agrobiodiversity, land productivity, resilience and adaptive capacities. Improving crop nutrient management is thus a perfect example of a win-win option supporting not only climate change mitigation, but also food security and nutrition, livelihoods and environmental sustainability (Smith et al. 2014; Mbow et al. 2019; HLPE 2019; Nabuurs et al. 2022). Innovative forms of fertilizers are also being explored, able to reduce significantly agricultural N2O emissions through the secretion of biological nitrification inhibitors (Mbow et al. 2019). In addition, improving energy-use efficiency in fertilizer manufacturing process could help further reduce the corresponding CO2 emissions intensity (per kg of fertilizer produced).

9 Improve rice cultivation

After livestock emissions, associated with enteric fermentation and manure management, rice cultivation has been constantly and consistently identified as an important source of farmgate CH4 emissions, associated with anaerobic conditions, by all the latest IPCC assessments (Smith et al. 2014; Jia et al. 2019; Nabuurs et al. 2022; see also Table 2). Livestock and rice emissions represent respectively 66% and 24% of agricultural CH4 emissions. 89% of CH4 emissions from rice cultivation originate from Asia and the share of that region still increases (Jia et al. 2019). Rice cultivation also generates N2O emissions through nitrification and denitrification. According to Gupta et al. (2021), around 11% of the total agricultural N2O emissions come from rice fields. The steady global increase in rice production,[50] which follows the world's population growth, has been recognized as a key driver of growing CH4 atmospheric concentration (Jia et al. 2019). This rising trend should continue in the future, but more slowly: over the next decade (2022-2031), rice production is expected to increase by about 10% (OECD/FAO 2022).

Mitigation options to reduce CH4 and N2O emissions associated with rice cultivation include improved water, straw residue, fertilizer and soil amendment management practices. Studies showed for instance that biochar application to paddy fields can generate significant reductions in N2O emissions (by up to 20 – 40%) and smaller reductions in CH4 emissions (Nabuurs et al. 2022). Improving rice cultivation practices can not only mitigate climate change but also enhance water-use efficiency, reduce production costs and improve yields, overall increasing rice farming system productivity, resilience and adaptive capacity. Beyond their contribution to climate change mitigation and adaptation, integrated production systems, such as rice-fish farming, can also reduce overall water needs, facilitate integrated pest management, and diversify sources of food and income (Mbow et al. 2019). Trade-offs can occur, however, between GHGs. For instance, on the one hand the introduction of multiple drainage practices, alternating wetting and drying, reduce water use by an estimated 25%, and CH4 emissions associated with wet conditions by 20 – 35%. On the other hand, these practices increase N2O emissions, associated with dry conditions, by about 20% (Nabuurs et al. 2022).

At the global level, improved rice cultivation holds a mitigation potential evaluated at 0.08-0.87 GtCO2eq per year (Roe et al. 2019), out of which 0.05 – 0.3 GtCO2eq per year could be available at carbon prices below USD 100 per tCO2eq (Nabuurs et al. 2022). Effective emission reductions are highly variable and heavily dependent on cultivation practices and soil and climate conditions. Hence, mitigation strategies and practices must be adapted to the local context (Nabuurs et al. 2022).

---

[50] According to FAOSTAT, between 1961 and 2021, global rice harvested area has increased by 43% while production has more than tripled from 216 to 787 million tons. See: https://www.fao.org/faostat/en/#data/QCL (accessed on 6 February 2023).

10 Increase soil organic carbon stock

10.1 Enhance soil carbon sequestration

The global mitigation potential of soil carbon sequestration (SCS) in mineral soils has been evaluated at 0.25 – 6.78 GtCO2 per year in croplands and 0.13 – 2.56 GtCO2 per year in grasslands (Roe et al. 2019). The corresponding economic potentials have been estimated at 0.4 – 0.9 GtCO2 per year in croplands and 0.3 – 1.6 GtCO2 per year in grasslands, at a carbon price below USD 100 per tCO2 (Nabuurs et al. 2022). Soil carbon is sequestered in croplands through improved crop management[51], improved nutrient and water management[52], and improved soil management[53] (Mbow et al. 2019; Nabuurs et al. 2022). In grasslands, SCS can occur through improved vegetation, livestock, manure and fire management practices[54] (Mbow et al. 2019; Nabuurs et al. 2022), and amendments with biochar (see next section). The SCS potential depends heavily on local soil and climate conditions in combination with land use and land management practices (Jia et al. 2019). The highest SCS potential lies in degraded croplands, which experienced important yield gaps or large historical losses in their soil organic carbon stock (Amelung et al. 2020), although very deteriorated soils may take more efforts to restore.

When compared to other carbon dioxide removal (CDR) options (such as bioenergy with carbon capture and storage or afforestation / reforestation), many SCS options may appear more feasible and socially more acceptable as they can be implemented with no change on land use and with negligible water and energy requirements (Fuss et al. 2018; de Coninck et al. 2018). Many SCS options are available at reasonable cost, ranging from 0 to 100 USD per tCO2 (Fuss et al. 2018). A raw calculation at global level shows that increasing soil organic carbon stocks by 4 per 1000 would be enough to offset anthropogenic emissions from fossil carbon (Minasny et al. 2017).[55] This observation gave rise to the '4 per 1000' international initiative, launched by France in 2015 during COP21 in Paris, which "encourages stakeholders to engage in a transition towards a regenerative, productive, highly resilient agriculture, based on appropriate land and soil management, which creates jobs and income and thus leads to sustainable development". This initiative "aims to show that agriculture can provide concrete solutions to the challenge posed by climate change while meeting the challenge of food security".[56]

Beyond mitigation, increasing soil organic carbon stock in mineral soils improves soil structure, health and productivity, nutrient availability and water retention capacity and supports soil microbial activity and biodiversity, thus boosting land productivity, resilience and adaptive capacity (FAO/ITPS 2015, IPBES 2018, Olsson et al. 2019). When accounting for these co-benefits for food security, livelihoods and biodiversity, SCS

---

[51] e.g., improved crop varieties, cover cropping, crop rotation, integrated and diversified cropping systems including perennial crops (e.g. agroforestry).

[52] For instance, through precision agriculture and drip irrigation.

[53] e.g., conservation agriculture, reduced tillage practices and residue retention.

[54] These practices include for instance: changes in vegetation composition (introduction of deep rooting or higher productivity grasses), changes in grazing intensity, fodder diversification, fire prevention or prescribed burning.

[55] Dividing the amount of global anthropogenic emissions from fossil carbon (estimated at 8.9 GtC) by the global soil carbon stock in the top 2m (estimated at 2,400 GtC) results in a value of 4 per 1000. Of course, this global value of 4 per 1000 cannot be applied everywhere as soil storage capacity depends on soil type and climate, as well as on land use and management (Minasny et al. 2017).

[56] For more information, see: https://4p1000.org/?lang=en

options may entail negative costs, as low as -45 USD per tCO2 (Fuss et al. 2018). This shows that an integrated perspective, considering all the dimensions of sustainable development, can facilitate the adoption of mitigation options such as SCS.

Yet, the global soil carbon sink is limited and itself vulnerable to future climate change (Jia et al. 2019). The IPCC considered that the maximum carbon storage potential in terrestrial ecosystems could be equivalent to the historical soil carbon loss induced by human activities, i.e. 180 ± 80 GtC (Clarke et al. 2014). However, Lal (2004a) found that SCS on agricultural and degraded land could store only up to 50 – 60% of the historical soil carbon loss (i.e. 42 – 58 GtC). In addition, soil erosion management and control can not only avoid GHG emissions (around 1.36 – 3.67 GtCO2 per year globally) but also enhance soil carbon sequestration thus creating an additional sink evaluated at 0.44 – 3.67 GtCO2 per year (Jia et al. 2019). However, such estimations remain very uncertain because of our limited knowledge of the final fate of the eroded material (Hoffmann et al. 2013).

10.2 Develop biochar amendments to soils

The biochar approach is derived as an isolated technique from research on Amazonian black soils, thought of indigenous origin (‘terra preta do Indio’), which possibly originated in a mixture of organic matter, carbon sources, and pottery shards. Identifying the key elements of this and developing this into a soil restoration technique is still subject to research (Glaser et al. 2001; Lehmann et al. 2003; Denevan & Woods 2007; Glaser and Birk 2012).

Amending soils with biochar, which is highly resistant to decomposition, help increase and stabilize soil organic carbon stocks (Jia et al. 2019; Olsson et al. 2019). The global mitigation potential of biochar application is evaluated in the range of 0.03 – 6.6 GtCO2eq per year (Roe et al., 2019; Jia et al. 2019; Olsson et al. 2019; Nabuurs et al. 2022), of which 0.3 – 1.8 GtCO2eq per year could be available at a carbon price below USD 100 per tCO2 (Nabuurs et al. 2022). The permanence of carbon stored through biochar application ranges from a few decades to thousands of years, depending on biochar production temperature, on the feedstock used and on soil properties (de Coninck et al. 2018, Olsson et al. 2019). In addition, the gases produced from biochar pyrolysis could be used for carbon capture and storage or as substitute to fossil energy sources, generating further GHG emission reductions (Smith 2016; Nabuurs et al. 2022). However, large-scale deployment of biochar application will require the production of dedicated feedstock, even if biochar is partly produced from residues, and, hence, will be constrained by costs (10 – 345 USD per tCO2; Babiker et al. 2022) and land requirements (16-100 Mha per GtCO2; Smith et al. 2015; Hoegh-Guldberg et al. 2018) although recent technological progresses could alleviate these constraints in the future (Olsson et al. 2019).

Like other SCS methods (see previous section), biochar application can help fighting land degradation and improving soil chemical, physical and biological properties (Lehmann et al. 2015; Olsson et al. 2019). Biochar application also facilitates biological nitrogen fixation and adsorption of organic pollutants and heavy metals and reduces odors from manure handling (Nabuurs et al. 2022). These agronomic co-benefits also impact biochar mitigation potential. In particular, by reducing nutrient leaching and volatilization from soils and increasing nutrient availability, biochar application not only improve land productivity but also reduce nutrient requirements and corresponding N2O emissions (Jia et al. 2019; Olsson et al. 2019; Nabuurs et al. 2022). On the other hand, some studies found that biochar application could increase CO2 and CH4 emissions from agricultural soils and provoke a rapid loss of soil organic carbon in the first decades (Wardle et al. 2008; Wang et al. 2012; IPCC 2013). Biochar application can also release black carbon dust and lower surface albedo inducing a warming effect, which can be limited if biochar is applied below the soil surface, in the form of pellets or granulates (Fuss et al. 2018; Jia et al. 2019; Olsson et al. 2019). Overall, there are still a lot of doubts on the benefits and risks of biochar application for soils and climate (The Royal Society 2018). To optimize its mitigation potential and agronomic co-benefits and limit its negative unintended effects, biochar formulation and application method needs to be adapted to the local context – including land use, plant needs, soil and climate conditions – (Olsson et al. 2019; Nabuurs et al. 2022).

11 Encourage agroforestry uptake and upscale

Agroforestry combines woody perennials (trees, shrubs, palms, bamboos, etc.) with crops and animals on the same land (Lundgren and Raintree, 1982). Based on a review of recent literature, the last IPCC assessment report (Nabuurs et al. 2022) estimated, with medium confidence, a global mitigation potential of 0.3 – 9.4 GtCO2eq per year for 2020 – 2050, of which 0.4 – 1.1 GtCO2eq per year could be available at carbon prices below USD 100 per tCO2eq. Those agroforestry systems which combine trees with perennial crops like cacao and coffee could hold a higher mitigation and carbon sink potential than those combining trees with annual crops (Mbow et al. 2019).

Beyond their carbon sequestration potential in vegetation and soils, trees in integrated agroforestry systems can provide multiple ecosystem services, such as: enhancing agrobiodiversity, providing habitats for pollinators and crop auxiliaries, providing shade and regulating local climate, improving soil health and structural stability, reducing soil erosion from wind and water, increasing microbial activity, improving nutrient and water circulation in soil and availability to crops thus increasing land productivity and ecosystem resilience. These multiple ecosystem services support all the four dimensions of food security and nutrition (availability, access, utilization and stability), as well as climate change mitigation and adaptation and many other SDGs (Gitz et al. 2021; Mbow et al. 2019; Nabuurs et al. 2022). Agroforestry systems must be adapted to the local biophysical and socio-economic conditions in order to maximize co-benefits and minimize risks. In particular, tree species need to be able to cope with future climate conditions.

12 Conclusion: what global potential for GHG emission reduction in food systems?

This paper suggests to adopt a holistic food system perspective when addressing global challenges such as climate change, food security, land degradation and biodiversity loss. The paper highlights the urgent need to address climate change by transforming the global food system and presents ten pathways towards low-carbon food systems that contribute to climate change mitigation while strengthening food security and the environment. While each topic represents a distinct area of focus, there are some overarching themes and conclusions that can be drawn from the various discussions.

Global warming since the pre-industrial era has reached almost 1.1°C, mainly driven by human activities. Time is short if the Paris Agreement targets of 1.5°C, or even 2°C, are to be respected. However, it is not too late. The global food systems, which account for 23 – 42 % of total anthropogenic emissions, which currently contributes to the problem, have to become part of the solution.

Of course, a lot of uncertainties and knowledge gaps remain that would require further research. However, there is enough evidence to act, based on what is already known. This will require technical and financial resources, political will and stakeholder engagement across sectors and scales.

This paper highlights ten promising pathways towards low-carbon food systems that contribute to climate change mitigation while strengthening food security and the environment. Each of these pathways gathers a range of sustainable techniques or practices, some of which would deserve to be further explored, while other can already be tested, implemented and upscaled at reasonable costs.

This paper identifies some synergies across development objectives. Mitigation options are more likely to be successfully implemented when the different development objectives, such as poverty reduction, food and water security, human health, clean energy, or biodiversity protection, are considered together and integrated in a holistic systems' thinking (Jakob et al. 2014; Niles et al. 2018). Similarly, this paper does not consider only supply or demand but the whole food value chain, from cradle to grave. Integrated multi-purpose options will not only provide more benefits for people and the planet but also will mobilize Green and Climate funds more easily as they will better match their requirements.

This paper also shows the very important mitigation potentials of demand-side options like changes in diets and reduction of food losses and waste. This highlights our individual and collective power as citizens and consumers to re-orient our food systems by changing our consumption habits and behaviors. It is not too late to reverse current trends and strive for a more sustainable future.

Overall, the solutions to climate change are complex and multifaceted, and that is even more true for the food system, a sector spanning across all the four conventional sectors considered in climate change mitigation action. Addressing this challenge will require a comprehensive approach that integrates both technological and social innovations, provides the needed technical and financial resources, as well as the needed policy reforms to drive this transformational change. It will require political will and also international cooperation to overcome the many challenges that stand in the way of progress in this field. Nevertheless, as the various pathways explored in this document demonstrate, perhaps there is cause for guarded optimism – taking a cross-sectoral approach may open up new avenues for concerted action.

This paper is a first attempt at mapping out the "territory". It does not (and cannot, at this stage) provide a detailed roadmap for how to achieve these changes. There are many uncertainties and large data and knowledge gaps that will require further research, not least in the area of properly addressing trade-offs, and costs of the various mitigation and adaptation options, reliable and trustworthy results and impact assessment. How to better integrate justice and equality considerations into climate action is not only a moral or ethical imperative but also one of efficiency and effectiveness: Measures taken against people's wills or interests will not move forward, and compromise will be needed, as interests differ. Yet, there is enough evidence to act based on what is already known. Through collaboration, scientists and practitioners will embark on generating the missing yet needed data that will ultimately also support evidence-based learning and course adjustment. We emphasize the importance of considering the different development objectives and integrating them into a holistic systems thinking to successfully implement mitigation and adaptation options throughout the whole food system.

References

Alexander, P., Brown, C., Arneth, A., Finnigan, J. & Rounsevell, M.D.A. 2016. Human appropriation of land for food: The role of diet. Global Environmental Change, 41, 88–98, https://doi.org/10.1016/J.GLOENVCHA.2016.09.005

Amelung, W., Bossio, D., de Vries, W., Kögel-Knabner, I., Lehmann, J., Amundson, R., Bol, R., Collins, C., Lal, R., Leifeld, J., Minasny, B., Pan, G., Paustian, K., Rumpel, C., Sanderman, J., van Groenigen, J.W., Mooney, S., van Wesemael, B., Wander, M. & Chabbi, A. 2020. Towards a global-scale soil climate mitigation strategy. Nature Communications (2020)11: 5427. https://doi.org/10.1038/s41467-020-18887-7

Amenchwi, A.G., Vanegas, M., Verchot, L. & Castro-Nunez, A. 2023. A Global Outlook of Greenhouse Gas Reduction Strategies and Policies Accross Different Levels of the Food System; a Review. Posted 18 Feb. 2023. 56p. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4363287

Angel, S., Parent, J., Civco, D.L., Blei, A. & Potere, D. 2011. The dimensions of global urban expansion: Estimates and projections for all countries, 2000-2050. Progress in Planning, 75(2), 53-107. https://doi.org/10.1016/j.progress.2011.04.001

Archimède, H., Eugène, M., Magdeleine, C.M., Boval, M., Martin, C., Morgavi, D.P., Lecomte, P. & Doreau, M. 2011. Comparison of methane production between C3 and C4 grasses and legumes. Animal Feed Science and Technology, 166, 59–64. https://doi.org/10.1016/j.anifeedsci.2011.04.003

Babiker, M., Berndes, G., Blok, K., Cohen, B., Cowie, A., Geden, O., Ginzburg, V., Leip, A., Smith, P., Sugiyama, M. & Yamba, F. 2022. Cross-sectoral perspectives. In: IPCC. 2022. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157926.005

Bai, X., Dawson, R.J., Ürge-Vorsatz, D., Delgado, G.C., Salisu Barau, A., Dhakal, S., Dodman, D., Leonardsen, L., Masson-Delmotte, V., Roberts, D.C. & Schultz, S. 2018. Six research priorities for cities and climate change. Nature, 555(7694), 23–25, https://doi.org/10.1038/d41586-018-02409-z

Barange, M., Bahri, T., Beveridge, M.C.M., Cochrane, K.L., Funge-Smith, S. & Poulain, F. 2018. Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options. FAO Fisheries and Aquaculture Technical Paper No. 627. Rome, Italy, 628 pp. https://www.fao.org/3/i9705en/I9705EN.pdf

Behfar, A., Yuill, D. & Yu, Y. 2018. Supermarket system characteristics and operating faults (RP-1615). Science and Technology for the Built Environment, 24(10), 1104–1113, https://doi.org/10.1080/23744731.2018.1479614

Brodt, S., Chernoh, E., & Feenstra, G. 2007. Assessment of energy use and greenhouse gas emissions in the food system: A literature review. Agricultural Sustainability Institute, University of California Davis. https://asi.ucdavis.edu/sites/g/files/dgvnsk5751/files/inline-files/litreview-assessmentofenergyuse.pdf

Clark, M.A., Domingo, N.G.G., Colgan, K., Thakrar, S.K., Tilman, D., Lynch, J., Azevedo, I.L. & Hill, J.D. 2020. Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets. Science Vol

370, No. 6517. https://doi.org/10.1126/science.aba7357

Clarke L., Jiang, K., Akimoto, K., Babiker, M., Blanford, G., Fisher-Vanden, K., Hourcade, J.-C., Krey, V., Kriegler, E., Löschel, A., McCollum, D., Paltsev, S., Rose, S., Shukla, P.R., Tavoni, M., van der Zwaan, B.C.C. & van Vuuren, D.P. 2014. Assessing Transformation Pathways. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter6.pdf

Coelho, P.M., Corona, B., ten Klooster, R. & Worrell, E. 2020. Sustainability of reusable packaging–Current situation and trends. Resources, Conservation & Recycling: X, 6, 100037. https://doi.org/10.1016/j.rcrx.2020.100037

Creutzig, F. 2016 Evolving Narratives of Low-Carbon Futures in Transportation. Transport Reviews, 36(3), 341–360, https://doi.org/10.1080/01441647.2015.1079277

Creutzig, F., Agoston, P., Minx, J.C., Canadell, J.G., Andrew, R.M., Le Quéré, C., Peters, G.P., Sharifi, A., Yamagata, Y. & Dhakal, S. 2016. Urban infrastructure choices structure climate solutions. Nature Climate Change, 6(12), 1054–1056, https://doi.org/10.1038/nclimate3169

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F.N. & Leip, A. 2021. Food systems are responsible for a third of global anthropogenic GHG emissions. Nature Food, 2, March 2021, 198-209. https://doi.org/10.1038/s43016-021-00225-9

Cristea, A., Hummels, D., Puzzello, L. & Avetisyan, M. 2013. Trade and the greenhouse gas emissions from international freight transport. Journal of Environmental Economics and Management, 65(1), 153–73. https://doi.org/10.1016/j.jeem.2012.06.002

Davis, S.J., Caldeira, K. & Matthews, H.D. 2010. Future CO2 Emissions and Climate Change from Existing Energy Infrastructure. Science 329, 1330 – 1333. https://doi.org/10.1126/science.1188566

de Coninck, H., Revi, A., Babiker, M., Bertoldi, P., Buckeridge, M., Cartwright, A., Dong, W., Ford, J., Fuss, S., Hourcade, J.-C., Ley, D., Mechler, R., Newman, P., Revokatova, A., Schultz, S., Steg, L., & Sugiyama, T. 2018. Strengthening and Implementing the Global Response. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre- industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 313-444. https://doi.org/10.1017/9781009157940.006.

Denevan, W.M. & Woods, W.I. 2007. Discovery and awareness of anthropogenic Amazonian dark earths (terra preta). http://www.eprida.com/eacu/PDF%20Files/BDenevan.pdf

DeRamus, H.A., Clement, T.C., Giampola, D.D. & Dickison, P.C. 2003. Methane emissions of beef cattle on forages: Efficiency of grazing management systems. Journal of Environmental Quality, 32(1), 269–277. https://doi.org/10.2134/jeq2003.2690

Dixson-Declève, S., Gaffney, O., Ghosh, J., Randers, J., Rockstrom, J., Stoknes, P.E., 2022. Earth for All: A Survival Guide for Humanity. New Society Publishers, Gabriola Island, British Columbia, Canada. https://www.clubofrome.org/publication/earth4all-book/

FAO (Food and Agricultural Organization of the United Nations). 2011a. Global food losses and food waste – extent, causes and prevention, by J. Gustavsson, C. Cederberg, U. Sonesson, R. van Otterdijk & A. Meybeck. Rome https://www.fao.org/3/mb060e/mb060e00.pdf

FAO. 2011b. “Energy-Smart” Food for People Climate- Issue Paper. Food and Agriculture Organization of the United Nations, Rome, Italy, 78 pp. https://www.fao.org/3/i2454e/i2454e.pdf

FAO. 2013a. Edible insects: future prospects for food and feed security. FAO Forestry paper 171. Rome. https://www.fao.org/3/i3253e/i3253e.pdf

FAO. 2013b. Food wastage footprint. Impacts on natural resources. Summary report. Rome. http://www.fao.org/3/i3347e/i3347e.pdf

FAO. 2014. Food wastage footprint. Full-cost accounting. Final report. Rome. http://www.fao.org/3/i3991e/i3991e.pdf

FAO. 2015. Food wastage footprint and climate change. 4p. Rome. http://www.fao.org/3/bb144e/bb144e.pdf

FAO. 2017. The future of food and agriculture – Trends and challenges. Rome. http://www.fao.org/3/a-i6583e.pdf

FAO. 2018a. The future of food and agriculture – Alternative pathways to 2050. Rome. 224 pp. http://www.fao.org/3/I8429EN/i8429en.pdf

FAO. 2018b. Our world is urbanizing. Is food on your agenda? http://www.fao.org/3/I8568EN/i8568en.pdf

FAO. 2019. The State of Food and Agriculture 2019. Moving forward on food loss and waste reduction. Food and Agriculture Organization of the United Nations, Rome, Italy. https://www.fao.org/3/ca6030en/ca6030en.pdf

FAO, IFAD, UNICEF, WFP & WHO. 2022. The State of Food Security and Nutrition in the World 2022. Repurposing food and agricultural policies to make healthy diets more affordable. Rome, FAO. https://doi.org/10.4060/cc0639en

FAO & ITPS. 2015. Status of the World's Soil Resources (SWSR) – Main Report. Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils, Rome, Italy. 650p. http://www.fao.org/3/a-i5199e.pdf

FAO & WHO. 2019. Sustainable Healthy Diets Guiding Principles. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy. https://www.fao.org/3/ca6640en/CA6640EN.pdf

Fischedick M., Roy, J., Abdel-Aziz, A., Acquaye, A., Allwood, J.M., Ceron, J.-P., Geng, Y., Kheshgi, H., Lanza, A., Perczyk, D., Price, L., Santalla, E., Sheinbaum, C. & Tanaka, K. 2014. Industry. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter10.pdf

Fixen, P.E. 2020. A brief account of the genesis of 4R nutrient stewardship. Agronomy Journal, 112(5), 4511-4518. https://doi.org/10.1002/agj2.20315

Fritzson A. & Berntsson, T. 2006. Energy efficiency in the slaughter and meat processing industry—opportunities for improvements in future energy markets. Journal of Food Engineering 77, 792–802. https://doi.org/10.1016/j.jfoodeng.2005.08.005

Fuss, S., Lamb, W.F., Callaghan, M.W. Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T., Luderer, G., Nemet, G.F., Rogelj, J., Smith, P., Vicente Vicente, J.L., Wilcox, J., del Mar Zamora Dominguez, M. and Minx, J.C. 2018. Negative emissions—Part 2: Costs, potentials and side effects. Environmental Research Letters 13, 063002. https://doi.org/10.1088/1748-9326/aabf9f

GBD (Global Burden of Disease) Collaborators. 2017. Health effects of overweight and obesity in 195 countries over 25 years. Published: 6 July 2017. The New England Journal of Medicine (2017), 377(1): 13–27. https://doi.org/10.1056/NEJMoa1614362

GBD Collaborators. 2019. Health effects of dietary risks in 195 countries, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. The Lancet (2019); 393: 1958–72. https://doi.org/10.1016/S0140-6736(19)30041-8

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A. & Tempio, G. 2013. Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations (FAO), Rome.

Gerhardt, C.F., Suhlmann, G., Ziemßen, F., Donnan, D.W., Warschun, M., & Kühnle, H.J. 2020. How Will Cultured Meat and Meat Alternatives Disrupt the Agricultural and Food Industry? Industrial Biotechnology, 16, 262-270. https://doi.org/10.1089/ind.2020.29227.cge

Gitz, V., Pingault, N., Meybeck, A., Ickowitz, A., McMullin, S., Sunderland, T., Vinceti, B., Powell, B., Termote, C., Jamnadass, R., Dawson, I. & Stadlmayr, B. 2021. Contribution of forests and trees to food security and nutrition. FTA Brief 5. Bogor, Indonesia: CIFOR. https://doi.org/10.17528/CIFOR/008006

Grainger, C., Clarke, T., Auldist, M.J., Beauchemin, K.A., Mc-Ginn, S.M., Waghorn, G.C. & Eckard, R.J. 2009. Potential use of Acacia mearnsii condensed tannins to reduce methane emissions and nitrogen excretion from grazing dairy cows. Canadian Journal of Animal Science, 89:241–251. https://doi.org/10.4141/CJAS08110

Grimm, N.B., Faeth, S.H., Golubiewski, N.E., Redman, C.L., Wu, J., Bai, X. & Briggs, J.M. 2008. Global change and the ecology of cities. Science, 319(5864), 756-760. New York, N.Y. https://doi.org/10.1126/science.1150195

Griscom, B.W., Adams, J., Ellis, P.W., Houghton, R.A., Lomax, G., Miteva, D.A., Schlesinger, W.H., Shoch, D., Siikamäki, J.V., Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R.T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M.R., Herrero, M., Kiesecker, J., Landis, E., Laestadius, L., Leavitt, S.M., Minnemeyer, S., Polasky, S., Potapov, P., Putz, F.E., Sanderman, J., Silvius, M., Wollenberg, E. & Fargione, J. 2017. Natural climate solutions. Proceedings of the National Academy of Sciences of the United States of America (PNAS), 114(44), 11645-11650. https://doi.org/10.1073/pnas.1710465114

Griscom, B., Busch, J., Cook-Patton, S.C., Ellis, P.W., Funk, J., Leavitt, S.M., Lomax, G., Turner, W.R., Chapman, M., Engelmann, J., Gurwick, N.P., Landis, E., Lawrence, D., Malhi, Y., Murray, L.S., Navarrete, D., Roe, S., Scull, S., Smith, P., Streck, C., Walker, W.S. & Worthington, T. 2020. National mitigation potential from natural climate solutions in the tropics. Philosophical Transactions of the Royal Society B: Biological Sciences, 375(1794), 20190126. https://doi.org/10.1098/rstb.2019.0126

Grubler, A., Bai, X., Buettner, T., Dhakal, S., Fisk, D., Ichinose, T., Keirstead, J., Sammer, G., Satterthwaite, D., Schulz, N., Shah, N., Steinberger, J. & Weisz, H. 2012. Urban Energy Systems. In: Global Energy Assessment: Toward a Sustainable Future (pp. 1307 – 1400). Cambridge University Press, Cambridge, UK. https://doi.org/10.1017/CBO9780511793677.024

Grübler, A. & Fisk, D. (eds). 2013. Energizing Sustainable Cities: Assessing Urban Energy. Abingdon, United Kingdom: Routledge. ISBN 9781849714396

Guo, X., Broeze, J., Groot, J.J., Axmann, H. & Vollebregt, M. 2020. A Worldwide Hotspot Analysis on Food Loss and Waste, Associated Greenhouse Gas Emissions, and Protein Losses. Sustainability, 12, 7488. https://doi.org/10.3390/su12187488

Gupta, K., Kumar, R., Baruah, K.K., Hazarika, S., Karmakar, S. & Bordoloi, N. 2021. Greenhouse gas emission from rice fields: a review from Indian context. Environmental Science and Pollution Research, 2021 Jun;28(24):30551-30572. https://doi.org/10.1007/s11356-021-13935-1

Hadjikakou, M. 2017. Trimming the excess: environmental impacts of discretionary food consumption in Australia. Ecological Economics, 131, 119–128, https://doi.org/10.1016/j.ecolecon.2016.08.006

Hasegawa, T., Fujimori, S., Havlík, P., Valin, H., Bodirsky, B.L., Doelman, J.C., Fellmann, T., Kyle, P., Koopman, J.F.L., Lotze-Campen, H., Mason-D'Croz, D., Ochi, Y., Pérez Domínguez, I., Stehfest, E., Sulser, T.B., Tabeau, A., Takahashi, K., Takakura, J., van Meijl, H., van Zeist, W.-J., Wiebe, K. & Witzke, P. 2018. Risk of increased food insecurity under stringent global climate change mitigation policy. Nature Climate Change 8, 699–703 (2018). https://doi.org/10.1038/s41558-018-0230-x

Heard, B.R. & Miller, S.A. 2016. Critical research needed to examine the environmental impacts of expanded refrigeration on the food system. Environmental Science & Technology, American Chemical Society, 50(22), 12060–12071. https://doi.org/10.1021/acs.est.6b02740

Hendrie, A.G., Baird, D., Ridoutt, B., Hadjikakou, M. & Noakes, M. 2016. Overconsumption of energy and excessive discretionary food intake inflates dietary greenhouse gas emissions in Australia. Nutrients, 8(11), 690. https://doi.org/10.3390/nu8110690

HLPE 2013. Biofuels and food security. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome 2013. https://www.fao.org/3/i2952e/i2952e.pdf

HLPE. 2014. Food losses and waste in the context of sustainable food systems. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome 2014. https://www.fao.org/3/i3901e/i3901e.pdf

HLPE. 2016. Sustainable agricultural development for food security and nutrition: what roles for livestock? A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. Rome. http://www.fao.org/3/a-i5795e.pdf

HLPE. 2017. Nutrition and food systems. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. https://www.fao.org/3/i7846e/i7846e.pdf

HLPE. 2018. Multi-stakeholder partnerships to finance and improve food security and nutrition in the framework of the 2030 Agenda. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. https://www.fao.org/3/CA0156EN/CA0156en.pdf

HLPE. 2019. Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome. https://www.fao.org/3/ca5602en/ca5602en.pdf

Hoegh-Guldberg, O., Jacob, D., Taylor, M., Bindi, M., Brown, S., Camilloni, I., Diedhiou, A., Djalante, R., Ebi, K.L., Engelbrecht, F., Guiot, J., Hijioka, Y., Mehrotra, S., Payne, A., Seneviratne, S.I., Thomas, A., Warren, R. & Zhou, G. 2018. Impacts of 1.5ºC Global Warming on Natural and Human Systems. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 175-312. https://doi.org/10.1017/9781009157940.005

Hoffmann, T., Mudd, S.M., van Oost, K., Verstraeten, G., Erkens, G., Lang, A., Middelkoop, H., Boyle, J., Kaplan, J.O., Willenbring, J. & Aalto, R. 2013. Short Communication: Humans and the missing C-sink: erosion and burial of soil carbon through time. Earth Surface Dynamics, 1, 45-52. https://doi.org/10.5194/ESURF-1-45-2013

Hooke, R.L. & Martín-Duque, J.F. 2012. Land transformation by humans: A review. GSA Today, 12(12), 4-10. https://doi.org/10.1130/GSAT151A.1

Hristov, A.N., Oh, J., Firkins, J.L., Dijkstra, J., Kebreab, E., Waghorn, G., Makkar, H.P., Adesogan, A.T., Yang, W., Lee, C., Gerber, P.J., Henderson, B. & Tricarico, J.M. 2013. SPECIAL TOPICS — Mitigation of methane and nitrous oxide emissions from animal operations. I. A review of enteric methane mitigation options. Journal of Animal Science, 91, 5045–5069, https://doi.org/10.2527/jas.2013-6583

Hristov, A.N., Oh, J., Giallongo, F., Frederick, T.W., Harper, M.T., Weeks, H.L., Branco, A.F., Moate, P.J., Deighton, M.H., Williams, S.R., Kindermann, M. & Duval, S. 2015. An inhibitor persistently decreased enteric methane emission from dairy cows with no negative effect on milk production. Proceedings of the National Academy of Sciences of the United States of America, 112, 10663–10668. https://doi.org/10.1073/pnas.1504124112

IIR (International Institute of Refrigeration). 2009. The role of refrigeration in worldwide nutrition – 5th Informatory note on refrigeration and food. Paris. https://iifiir.org/en/fridoc/the-role-of-refrigeration-in-worldwide-nutrition-2009-131376

IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services). 2018: The IPBES assessment report on land degradation and restoration. Montanarella, L., Scholes, R., and Brainich, A. (eds.). Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany. 744 pages. https://ipbes.net/sites/default/files/2018_ldr_full_report_book_v4_pages.pdf

IPCC (Intergovernmental Panel on Climate Change). 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan. https://www.ipcc-nggip.iges.or.jp/public/2006gl/l

IPCC. 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovermental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_all_final.pdf

IPCC. 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp. https://archive.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full_wcover.pdf

IPCC. 2018. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. https://www.ipcc.ch/sr15/download/

IPCC. 2019a. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Accepted in May 2019. https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/

IPCC. 2019b. Summary for Policymakers. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.- O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. https://doi.org/10.1017/9781009157988.001

IPCC. 2021. Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3–32. https://doi.org/10.1017/9781009157896.001

IPES-Food. 2016. From uniformity to diversity. A paradigm shift from industrial agriculture to diversified agroecological systems. International Panel of experts on sustainable food systems. http://www.ipes-food.org/_img/upload/files/UniformityToDiversity_FULL.pdf

James, S.J., and James, C. 2010. The food cold-chain and climate change. Food Research International, 43(7), 1944–1956, https://doi.org/10.1016/j.foodres.2010.02.001

Jaramillo, P., Kahn Ribeiro, S., Newman, P., Dhar, S., Diemuodeke, O.E., Kajino, T., Lee, D.S., Nugroho, S.B., Ou, X., Hammer Strømman, A. & Whitehead, J. 2022. Transport. In: IPCC. 2022. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija,

G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157926.012

Jia, G., Shevliakova, E., Artaxo, P., De Noblet-Ducoudré, N., Houghton, R., House, J., Kitajima, K., Lennard, C., Popp, A., Sirin, A., Sukumar, R. & Verchot, L. 2019. Chapter 2: Land–climate interactions. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M, Belkacemi & J. Malley (eds.). https://doi.org/10.1017/9781009157988.004

Joseph, S., Cowie, A.L., Van Zwieten, L., Bolan, N., Budai, A., Buss, W., Cayuela, M.-L., Graber, E.R., Ippolito, J.A., Kuzyakov, Y., Luo, Y., Sik Ok, Y., Palansooriya, K.N., Shepherd, J., Stephens, S., Weng, Z.H. & Lehmann, J. 2021. How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar. GCB Bioenergy, 13(11), 1731–1764, https://doi.org/10.1111/gcbb.12885

Kriewald, S., Pradhan, P., Costa, L., Cantu, R.A. & Kropp, J. 2019. Hungry cities: how local food self-sufficiency relates to climate change, life styles and demographic development. Environmental Research Letters, 14(2019), 094007, https://doi.org/10.1088/1748-9326/ab2d56

Kumar, P., Chatli, M.K., Mehta, N., Singh, P., Malav, O.P. & Verma, A.K. 2017. Meat analogues: Health promising sustainable meat substitutes. Critical Reviews in Food Science and Nutrition, 57(5), 923–932, https://doi.org/10.1080/10408398.2014.939739

Kummu, M., de Moel, H., Porkka, M., Siebert, S., Varis, O. & Ward, P.J. 2012. Lost food, wasted resources: Global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use. Science of The Total Environment 438, 477-489. https://doi.org/10.1016/j.scitotenv.2012.08.092

Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. Science, 304, 1623–1627. https://doi.org/10.1126/science.1097396

Leger, D., Matassa, S., Noor, E., Shepon, A., Milo, R. & Bar-Even, A. 2021. Photovoltaic-driven microbial protein production can use land and sunlight more efficiently than conventional crops. Proceedings of the National Academy of Sciences of the United States of America (PNAS), 118(26), e2015025118. https://doi.org/10.1073/pnas.2015025118

Lehmann, J., Kuzyakov, Y., Pan, G. & Ok, Y.S. 2015: Biochars and the plant-soil interface. Plant Soil, 395, 1–5, https://doi.org/10.1007/s11104-015-2658-3

Liu, Z., He, C., Zhou, Y. & Wu, J. 2014. How much of the world's land has been urbanized, really? A hierarchical framework for avoiding confusion. Landscape Ecology, 29, 763-771. https://doi.org/10.1007/s10980-014-0034-y

Lotze-Campen, H., von Lampe, M., Kyle, P., Fujimori, S., Havlik, P., van Meijl, H., Hasegawa, T., Popp, A., Schmitz, C., Tabeau, A., Valin, H., Willenbockel, D. & Wise, M. 2013. Impacts of increased bioenergy demand on global food markets: an AgMIP economic model intercomparison. Agricultural Economics, 45 (1), 103-116. https://doi.org/10.1111/agec.12092

Lundgren, B.O. & Raintree, J.B. 1982. Sustained agroforestry. In B. Nestel, ed. Agricultural research for development: potentials and challenges in Asia, pp. 37–49. The Hague, ISNAR.

Lwasa, S., Seto, K.C., Bai, X., Blanco, H., Gurney, K.R., Kılkış, Ş., Lucon, O., Murakami, J., Pan, J., Sharifi, A. & Yamagata, Y. 2022. Urban systems and other settlements. In: IPCC. 2022. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157926.010

Lynch, K. & Rodwin, L. 1958. A Theory of Urban Form. Journal of the American Institute of Planners, 24(4), 201-214, https://doi.org/10.1080/01944365808978281

March Consulting Group. 1998. Opportunities to minimize emissions of hydrofluorocarbons (HFCs) in the European union. Final report prepared by March Consulting Group, UK. 30th September 1998. https://ec.europa.eu/docsroom/documents/12170/attachments/1/translations/en/renditions/native

Mbow, C., Rosenzweig, C., Barioni, L.G., Benton, T.G., Herrero, M., Krishnapillai, M., Liwenga, E., Pradhan, P., Rivera-Ferre, M.G., Sapkota, T., Tubiello, F.N. & Xu, Y. 2019. Food Security. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. https://doi.org/10.1017/9781009157988.007

McLinden, M.O., Brown, J.S., Brignoli, R., Kazakov, A.F. & Domanski, P.A. 2017. Limited options for low-global-warming-potential refrigerants. Nature Communications, 8(1), 1–9, https://doi.org/10.1038/ncomms14476

Meemken, E.-M. & Qaim, M. 2018. Organic agriculture, food security, and the environment. Annual Review of Resource Economics, 10, 39-63. https://doi.org/10.1146/annurev-resource-100517-023252

Mekonnen, M.M. & Hoekstra, A.Y. 2011. The green, blue and grey water footprint of crops and derived crop products, Hydrology and Earth System Sciences, 15(5): 1577-1600. https://doi.org/10.5194/hess-15-1577-2011

Mekonnen, M.M. & Hoekstra, A.Y. 2012. A global assessment of the water footprint of farm animal products, Ecosystems, 15(3): 401–415. https://doi.org/10.1007/s10021-011-9517-8

Mekonnen, M.M. & Hoekstra, A.Y. 2015. Global Gray Water Footprint and Water Pollution Levels Related to Anthropogenic Nitrogen Loads to Fresh Water. Environmental Science & Technology, 49(21), 12860-12868. https://doi.org/10.1021/acs.est.5b03191

Meybeck, A. & Gitz, V. 2017. Sustainable diets within sustainable food systems. Proceedings of the Nutrition Society, 76(1), 1–11, https://doi.org/10.1017/S0029665116000653

Minasny, B., Malone, B.P., McBratney, A.B., Angers, D.A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z.-S. Cheng, K., Das, B.S., Field, D.J., Gimona, A., Hedley, C.B., Young Hong, S., Mandal, B., Marchant, B.P., Martin, M., McConkey, B.G., Leatitia Mulder, V., O'Rourke, S., Richer-de-Forges, A.C., Odeh, I., Padarian, J., Paustian, K., Pan, G., Poggio, L., Savin, I., Stolbovoy, V., Stockmann, U., Sulaeman, Y., Tsui, C.-C., Vågen, T.-G., van Wesemael, B. & Winowiecki, L. 2017. Soil carbon 4 per mille. Geoderma, 292, 59-86. https://doi.org/10.1016/j.geoderma.2017.01.002

Molina-Besch, K., Wikström, F. & Williams, H. 2019. The environmental impact of packaging in food supply chains—does life cycle assessment of food provide the full picture? The International Journal of Life Cycle Assessment, 24(1), 37–50, https://doi.org/10.1007/s11367-018-1500-6

Montes, F., Meinen, R., Dell, C., Rotz, A., Hristov, A.N., Oh, J., Waghorn, G., Gerber, P.J., Henderson, B. & Makkar, H.P.S. 2013. SPECIAL TOPICS — Mitigation of methane and nitrous oxide emissions from animal operations: II. A review of manure management options. Journal of Animal Science, 91, 5070–5094. https://doi.org/10.2527/jas.2013-6584

Nabuurs, G-J., Mrabet, R., Abu Hatab, A., Bustamante, M., Clark, H., Havlík, P., House, J., Mbow, C., Ninan, K.N., Popp, A., Roe, S., Sohngen, B. & Towprayoon, S. 2022. Agriculture, Forestry and Other Land Uses (AFOLU). In: IPCC. 2022. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157926.009

Niles, M.T., Ahuja, R., Barker, T., Esquivel, J., Gutterman, S., Heller, M.C., Mango, N., Portner, D., Raimond, R., Tirado, C. & Vermeulen, S. 2018. Climate change mitigation beyond agriculture: a review of food system opportunities and implications. Renewable Agriculture and Food Systems, 33(3), 297–308, https://doi.org/10.1017/S1742170518000029

OECD/FAO. 2022. OECD-FAO Agricultural Outlook 2022-2031. OECD Publishing, Paris, https://doi.org/10.1787/f1b0b29c-en

Olsson, L., Barbosa, H., Bhadwal, S., Cowie, A., Delusca, K., Flores-Renteria, D., Hermans, K., Jobbagy, E., Kurz, W., Li, D., Sonwa, D.J. & Stringer, L. 2019. Land Degradation. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. https://doi.org/10.1017/9781009157988.006

Pendrill, F., Persson, U.M., Godar, J. & Kastner, T. 2019. Deforestation displaced: trade in forest-risk commodities and the prospects for a global forest transition. Environmental Research Letters, 14(5), 055003. https://doi.org/10.1088/1748-9326/ab0d41

Pesaresi, M., Melchiorri, M., Siragusa, A. and Kemper, T. 2016. Atlas of the Human Planet 2016: Mapping Human Presence on Earth with the Global Human Settlement Layer. European Commission. http://publications.jrc.ec.europa.eu/repository/bitstream/JRC103150/atlas%20of%20the%20human%20planet_2016_online.pdf

Pikaar, I., Matassa, S., Rabaey, K., Laycock, B., Boon, N. & Verstraete, W. 2018. The Urgent Need to Re-engineer Nitrogen-Efficient Food Production for the Planet. In: Managing Water, Soil and Waste Resources to Achieve Sustainable Development Goals. [Hülsmann, S. & Ardakanian, R. (eds)]. Springer International Publishing, Cham, 35–69 http://doi.org/10.1007/978-3-319-75163-4_3

Poore, J., & Nemecek, T. 2018. Reducing food's environmental impacts through producers and consumers. Science, 360(6392), 987-992. https://doi.org/10.1126/science.aaq0216

Porter, S.D., Reay, D.S. Higgins, P. & Bomberg, E. 2016. A half-century of production-phase greenhouse gas emissions from food loss & waste in the global food supply chain. Science of the Total Environment, 571, 721-729. https://doi.org/10.1016/j.scitotenv.2016.07.041

Pörtner, H.O., Scholes, R.J., Agard, J., Archer, E., Arneth, A., Bai, X., Barnes, D., Burrows, M., Chan, L., Cheung, W.L., Diamond, S., Donatti, C., Duarte, C., Eisenhauer, N., Foden, W., Gasalla, M. A., Handa, C., Hickler, T., Hoegh-Guldberg, O., Ichii, K., Jacob, U., Insarov, G., Kiessling, W., Leadley, P., Leemans, R., Levin, L., Lim, M., Maharaj, S., Managi, S., Marquet, P. A., McElwee, P., Midgley, G., Oberdorff, T., Obura, D., Osman, E., Pandit, R., Pascual, U., Pires, A. P. F., Popp, A., Reyes-García, V., Sankaran, M., Settele, J., Shin, Y. J., Sintayehu, D. W., Smith, P., Steiner, N., Strassburg, B., Sukumar, R., Trisos, C., Val, A.L., Wu, J., Aldrian, E., Parmesan, C., Pichs-Madruga, R., Roberts, D.C., Rogers, A.D., Díaz, S., Fischer, M., Hashimoto, S., Lavorel, S., Wu, N. & Ngo, H.T. 2021. Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change. IPBES secretariat, Bonn, Germany, https://doi.org/10.5281/zenodo.4659158

Roe, S., Streck, C., Obersteiner, M., Frank, S., Griscom, B., Drouet, L., Fricko, O., Gusti, M., Harris, N., Hasegawa, T., Hausfather, Z., Havlík, P., House, J., Nabuurs, G.J., Popp, A., Sanz Sánchez, M.J., Sanderman, J., Smith, P., Stehfest, E., & Lawrence, D. 2019. Contribution of the land sector to a 1.5 °C world. Nature Climate Change, Vol 9, (Nov. 2019):817-828. https://doi.org/10.1038/s41558-019-0591-9

Roe, S., Streck, C., Beach, R., Busch, J., Chapman, M., Daioglou, V., Deppermann, A., Doelman, J., Emmet-Booth, J., Engelmann, J., Fricko, O., Frischmann, C., Funk, J., Grassi, G., Griscom, B., Havlik, P., Hanssen, S., Humpenöder, F., Landholm, D., Lomax, G., Lehmann, J., Mesnildrey, L., Nabuurs, G.-J., Popp, A., Rivard, C., Sanderman, J., Sohngen, B., Smith, P., Stehfest, E., Woolf, D.

& Lawrence, D. 2021. Land-based measures to mitigate climate change: Potential and feasibility by country. Global Change Biology, 27, 6025–6058. https://doi.org/10.1111/gcb.15873

Ruane, A.C., Antle, J., Elliott, J., Folberth, C., Hoogenboom, G., Mason-D'Croz, D., Müller, C., Porter, C., Phillips, M.M., Raymundo, R.M., Sands, R., Valdivia, R.O., White, J.W., Wiebe & K., Rosenzweig, C. 2018: Biophysical and economic implications for agriculture of +1.5° and +2.0°C global warming using AgMIP Coordinated Global and Regional Assessments. Climate Research, 76(1), 17–39, https://doi.org/10.3354/cr01520

Seto K. C., Dhakal, S., Bigio, A., Blanco, H., Delgado, G.C., Dewar, D., Huang, L., Inaba, A., Kansal, A., Lwasa, S., McMahon, J.E., Müller, D.B., Murakami, J., Nagendra, H. & Ramaswami, A. 2014. Human Settlements, Infrastructure and Spatial Planning. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter12.pdf

Seto, K.C. Davis, S.J., Mitchell, R.B., Stokes, E.C., Unruh, G. & Ürge-Vorsatz, D. 2016: Carbon Lock-In: Types, Causes, and Policy Implications. Annual Review of Environment and Resources, 41, 425–452, https://doi.org/10.1146/annurev-environ-110615-085934

Seto, K.C., Güneralp, B. & Hutyra, L.R. 2012. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. Proceedings of the National Academy of Sciences of the United States of America (PNAS), 109(40): 16083–16088. https://doi.org/10.1073/pnas.1211658109

Sinclair, F. & Coe, R. 2019. The Options by Context Approach: A Paradigm Shift in Agronomy. Exp. Agric., 55(S1), 1–13, https://doi.org/10.1017/S0014479719000139

Smith, P. 2016. Soil carbon sequestration and biochar as negative emission technologies. Global Change Biology, 22, 1315–1324, https://doi.org/10.1111/gcb.13178

Smith P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Haberl, H., Harper, R., House, J., Jafari, M., Masera, O., Mbow, C., Ravindranath, N.H., Rice, C.W., Robledo Abad, C., Romanovskaya, A., Sperling, F. & Tubiello, F. 2014. Agriculture, Forestry and Other Land Use (AFOLU). In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter11.pdf

Smith, P., Calvin, K., Nkem, J., Campbell, D., Cherubini, F., Grassi, G., Korotkov, V., Hoang, A. L., Lwasa, S., McElwee, P., Nkonya, E., Saigusa, N., Soussana, J. F., Taboada, M. A., Manning, F. C., Nampanzira, D., Arias-Navarro, C., Vizzarri, M., House, J., & Arneth, A. 2020. Which practices co-deliver food security, climate change mitigation and adaptation, and combat land degradation and desertification? Global Change Biology, 26(3), 1532–1575. https://doi.org/10.1111/gcb.14878

Smith, P., Davis, S.J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R.B., Cowie, A., Kriegler, E., van Vuuren, D.P., Rogelj, J., Ciais, P., Milne, J., Canadell, J.G., McCollum, D., Peters, G., Andrew, R., Krey, V., Shrestha, G., Friedlingstein, P., Gasser, T., Grübler, A., Heidug, W.K., Jonas, M., Jones, C.D., Kraxner, F., Littleton, E., Lowe, J., Roberto Moreira, J., Nakicenovic, N., Obersteiner, M., Patwardhan, A., Rogner, M., Rubin, E., Sharifi, A., Torvanger, A., Yamagata, Y., Edmonds, J. & Yongsung, C. 2015. Biophysical and economic limits to negative CO2 emissions. Nature Climate Change, 6(1), 42–50, https://doi.org/10.1038/nclimate2870

Springmann, M., Godfray, H. C. J., Rayner, M. & Scarborough, P. 2016. Analysis and valuation of the health and climate change co-benefits of dietary change. Proceedings of the National Academy of Sciences of the United States of America (PNAS), 113, 4146–4151. https://doi.org/10.1073/pnas.1523119113

Springmann, M., Mason-D'Croz, D., Robinson, S., Wiebe, K., Godfray, H.C.J., Rayner, M. & Scarborough, P. 2017. Mitigation potential and global health impacts from emissions pricing of food commodities. Nature Climate Change, 7, 69–74. https://doi.org/10.1038/nclimate3155

Tassou, S.A., De-Lille, G., & Ge, Y.T. 2008. Food transport refrigeration – Approaches to reduce energy consumption and environmental impacts of road transport. Applied Thermal Engineering, 29(8–9), 1467–1477. https://doi.org/10.1016/J.APPLTHERMALENG.2008.06.027

Tassou, S.A., Lewis, J., Ge, Y.T., Hadawey, A., & Chae, I. 2009. A review of emerging technologies for food refrigeration applications. Applied Thermal Engineering, 30(4), 263-276. https://doi.org/10.1016/j.applthermaleng.2009.09.001

The Royal Society. 2018: Greenhouse gas removal. 136 pp. https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf

Thebo, A.L., Drechsel, P. & Lambin, E.F. 2014. Global assessment of urban and peri-urban agriculture: irrigated and rainfed croplands. Environmental Research Letters, 9(11), 114002. https://doi.org/10.1088/1748-9326/9/11/114002

Theurl, M. C., Haberl, H., Erb, K.-H. & Lindenthal, T. 2014. Contrasted greenhouse gas emissions from local versus long-range tomato production. Agronomy for Sustainable Development, 34, 593–602, https://doi.org/10.1007/s13593-013-0171-8

Tittonell, P., van Wijk, M.T., Herrero, M., Rufino, M.C., de Ridder, N. & Giller, K.E. 2009. Beyond resource constraints - Exploring the biophysical feasibility of options for the intensification of smallholder crop-livestock systems in Vihiga district, Kenya. Agricultural Systems, 101 (1-2), 1-19. https://doi.org/10.1016/j.agsy.2009.02.003

Tsilini, V., Papantoniou, S., Kolokotsa, D.-D. & Maria, E.-A. 2015. Urban gardens as a solution to energy poverty and urban heat island. Sustainable Cities and Society, 14, 323–333, https://doi.org/10.1016/J.SCS.2014.08.006

UN (United Nations). 2015. Transforming our world: the 2030 agenda for sustainable development. A/RES/70/1. New York, USA. https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf

UNDESA (United Nations, Department of Economic and Social Affairs, Population Division). 2019. World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420). New York: United Nations. https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf

UNEP (United Nations Environment Programme). 2019. Global Environment Outlook. GEO environment for development 6. http://www.unep.org/global-environment-outlook

van Horn, H.H. 1998. Factors affecting manure quantity, quality and use. Department of Dairy and Poultry Sciences. University of Florida. Gainesville. https://www.txanc.org/proceedings/1998/vanhorn3.pdf

van Vliet, J., Eitelberg, D.A. & Verburg, P.H. 2017. A global analysis of land take in cropland areas and production displacement from urbanization. Glob. Environ. Change, 43, 107–115, https://doi.org/10.1016/j.gloenvcha.2017.02.001

Vieux, F., Darmon, N., Touazi, D. & Soler, L. 2012. Greenhouse gas emissions of self-selected individual diets in France: changing the diet structure or consuming less? Ecological Economics 75, 91–101. https://doi.org/10.1016/j.ecolecon.2012.01.003

Wang, L. 2013. Energy consumption and reduction strategies in food processing. In: Sustainable Food Processing [Tiwari, B.K., Norton, T., & Holden, N.M. (eds)]. Chichester, UK: John Wiley & Sons, Ltd. https://doi.org/10.1002/9781118634301.ch16

Wang, J., X. Pan, Y. Liu, X. Zhang, and Z. Xiong. 2012. Effects of biochar amendment in two soils on greenhouse gas emissions and crop production. Plant Soil, 360, 287–298. https://doi.org/10.1007/s11104-012-1250-3

Wardle, D.A., Nilsson, M.-C. & Zackrisson, O. 2008. Fire-derived charcoal causes loss of forest humus. Science, 320, 629. https://doi.org/10.1126/science.1154960

WB & FAO. 2017. Food systems for an urbanizing world. Tefft, J., Jonasova, M., Adjao, R. & Morgan, A. (eds). Knowledge product. November 2017. World Bank Group, Food and Agriculture Organization of the United Nations. http://documents.worldbank.org/curated/en/454961511210702794/pdf/Food-Systems-for-an-Urbanizing-World.pdf

Weiler, V., Udo, H.M.J., Viets, T., Crane, T.A. & De Boer, I.J.M. 2014. Handling multi-functionality of livestock in a life cycle assessment: The case of smallholder dairying in Kenya. Current Opinion in Environmental Sustainability, 8, 29–38, https://doi.org/10.1016/j.cosust.2014.07.009

Westhoek, H., Lesschen, J.P., Rood, T., Wagner, S., DeMarco, A., Murphy-Bokern, D., Leip, A., van Grinsven, H., Sutton, M.A. & Oenema, O. 2014. Food choices, health and environment: Effects of cutting Europe’s meat and dairy intake. Global Environmental Change, 26, 196–205, https://doi.org/10.1016/j.gloenvcha.2014.02.004

WHO (World Health Organization). 2019. Health taxes: a primer. World Health Organization, Geneva, Switzerland. https://www.who.int/publications/i/item/WHO-UHC-HGF-PolicyBrief-19.7

Willett, W. Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L.J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J.A., De Vries, W., Majele Sibanda, L., Afshin, A., Chaudhary, A., Herrero, M., Agustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S.E., Srinath Reddy, K., Narain, S., Nishtar, S. & Murray, C.J.L. 2019. Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. The Lancet (London, England), 393, 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4

DOI: 10.17528/cifor-icraf/008836

Global average surface temperatures are now 1.09°C higher than in pre-industrial era, with greenhouse gas emissions (GHGE) from human activities unequivocally identified as the main driver behind this global warming. In 2018, the global food system emitted 13-23 GtCO2eq per year, or 23-42% of total net anthropogenic emissions. Without a radical transformation of the food system, it may be impossible to reach the Paris Agreement goal of limiting global warming to 1.5/2.0°C. Following the IPCC guidelines, data on GHG emissions are generally collected and analyzed by economic sectors (Energy, Industry, AFOLU, Waste). Moving away from this sectoral perspective, this paper suggest to adopt a holistic view covering the whole food supply chain from farm to fork. This paper reviews ten promising pathways to GHG emission reduction in food systems: shifting diets; improving waste management, energy use in value chains, cold-chain efficiency; reducing enteric fermentation; improving manure management, fertilizer manufacturing emissions, rice cultivation, soil organic carbon; and encouraging agroforestry. It assesses their technical and economic mitigation potentials, the synergies and trade-offs across mitigation options and development goals, as well as the stumbling blocks for implementation, and suggests ways forward. These suggested pathways are intended to trigger a debate and open up avenues to a rapid drawdown of GHG emissions, by taking a holistic view to the global food system, one of the largest GHG-emitting sectors in the planet. This paper shows the very important mitigation potentials of demand-side options like changes in diets and reduction of food losses and waste. This highlights our individual and collective power as citizens and consumers to re-orient our food systems by changing our consumption habits and behaviors. It is not too late.

cifor-icraf.org

cifor.org | worldagroforestry.org

CGIAR

Mitigate+: Research
for Low-Emission
Food Systems